Met. O. 903

METEOROLOGICAL OFFICE

Scientific Paper No. 39

A Comparative Study of some Single Pole Visibility Sensors, the Meteorological Office Mk 4 Transmissometer and Estimates of Visibility made by Observers

by F. S. Bond, J. S. Foot, Ph.D and R. E. W. Pettifer, Ph.D.

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SUMMARY

This study was conducted in response to the need to find visibility sensors suitable for use on automatic weather stations and for mounting at a single point. It aimed at establishing whether or not each of three different measurement techniques was intrinsically satisfactory for making visibility measurements, whether or not, when used in an operational role, instruments based upon these techniques would yield unambiguous and valid visibility data, and whether the particular instruments used exhibited any significant functional weaknesses.

The instruments used for this work were the Erwin Sick SM 414 and the Marconi MET 1 short-base-line transmissometers, the M.R.I. Fog Visiometer (a scattering nephelometer) and the Plessey Point Visibility Meter (a forward-scatter device).

To provide a frame of reference for the work we compared each instrument with the standard Meteorological Office Mk 4 (200 m base-line) transmissometer which we also compared with estimates of visibility made by day and by night by unaided observers who did not know that the comparison was under way.

We have shown that the calibration procedure for the Mk 4 transmissometer is inadequate in principle and recommendations are made for an improved procedure.

Clear evidence is presented to show that the quality of the estimates of visibility made by unaided observers deteriorated significantly at night and that the Mk 4 transmissometer provided estimates of meteorological optical range which were as good as those of observers by day and better by night.

Comparisons between the Mk 4 transmissometer and two short-base-length, folded-path devices showed that the Marconi MET 1 performed in a manner very similar to the Mk 4 but that the Erwin Sick SM 414 showed significant differences from it.

Studies were made of two scattering instruments, the M.R.I. Fog Visiometer and the Plessey Point Visibility Meter. It was concluded that although, in principle, scattering instruments can provide estimates of visibility as good as those of transmissometers, neither of these instruments was satisfactory.

The M.R.I. device exhibited serious instrumental shortcomings and yielded poor results under operational conditions. The Plessey PVM sampled such a small volume of the atmosphere that only a rapid sampling and data-filtering technique could yield results comparable to those of a transmissometer. Furthermore, in conditions of fog and light wind the device exhibited an inverse relationship between wind speed and visibility which was traced to thermal coupling between the instrument and the fog. This effect resulted in a significant modification of the fog in the sample volume and therefore in incorrect visibility measurements.

A series of recommendations about the operational aspects of visibility measurement devices forms the final part of the report.

1. INTRODUCTION

Hitherto the only approved instrumental aids for visibility measurements made within the Meteorological Office have been the Gold visibility meter (Meteorological Office 1956a)

and the Mk 4 transmissometer (Meteorological Office 1956b). The Gold visibility meter requires an observer to operate it and is very dependent upon the quality of the individual calibration of each observer; the Mk 4 transmissometer is a very large device which requires an unobstructed base-line of 200 m and substantial concrete plinths for mounting the transmitter and receiver units. It further requires regular calibration by an observer in conditions of good visibility (see sections 3.1 and 5.1.2.1). Clearly neither of these instruments can reasonably be used on automatic weather stations designed for long-term, unattended operation on small, remote sites and the transmissometer has serious disadvantages for installation anywhere. It has therefore become necessary to consider techniques and instruments for making 'single pole' visibility measurements, that is to say, measurements made over paths sufficiently short that the instrument involved can be mounted at a single point.

The investigations reported here were undertaken with the aim of establishing whether or not each of three different measurement techniques is intrinsically satisfactory for making visibility measurements; whether or not, when used in an operational role, instruments based on these techniques would yield unambiguous and valid visibility data of the type normally required in synoptic meteorology and whether the particular instruments used in this work exhibited any significant functional weaknesses.

The instruments used for the study were the Erwin Sick short-base-line transmissometer, the Marconi short-base-line transmissometer, the M.R.I.* Fog Visiometer and the Plessey Point Visibility Meter (PVM). The first two of these rely on the measurement of the atmospheric extinction coefficient over a short (about 3 m) base length but are otherwise similar in concept to the Mk 4 transmissometer. The Fog Visiometer is an integrating nephelometer with an acceptance angle for scattering in the range $8° - 170°$ and the Plessey PVM is an instrument which measures forward-scattered light from a very small sample volume.

The experimental approach adopted has been to examine the performance of each instrument relative to that of the Mk 4 transmissometer with the circumstances of the measurements chosen so as to emphasize the particular experimental objective under scrutiny. To study the physical principles of each instrument as nearly as possible free from the complications of atmospheric variability, restricted sets of data were examined which were obtained in well-mixed fog or haze conditions; to study the operational certainty of the instrumental information, data sets were obtained without regard to the prevailing conditions. In addition, some studies of the spatial and temporal variations of visibility and the extent to which these can be reliably filtered were conducted. The performance characteristics, strengths and weaknesses, of the devices used were noted during the course of the work and are commented upon as appropriate, in particular a detailed study was made of the way in which the PVM affects the sample of the atmosphere at which it looks.

In order to provide a common standard for the comparisons, each instrument was compared with the standard Mk 4 transmissometer. Since the measurements extended over many months, close attention had to be paid to the calibration of this instrument and to the way in which the calibration changed. This led to some new information about the transmissometer and the calibration techniques used for it, which is discussed in section 5

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of this paper. To provide a familiar context within which to judge the performance of all the instruments, information was sought about how the Mk 4 transmissometer compared with trained observers in their estimates of reportable visibility. Several studies of this type have been done but the measure of agreement between them is not striking and in some cases 'fudge factors' were required in order to explain systematic differences in the results. In view of this, the output from the Mk 4 used in this work was compared with the estimate of visibility made by the trained observers at Beaufort Park and an analysis of these results showed that, after allowing for all the sources of error in the results, the Mk 4 performed very satisfactorily. These results are given and discussed in section 5.1.

2. THE THEORY OF VISIBILITY MEASUREMENTS

According to the introductory paragraphs of Chapter 3 of the *Observer's Handbook* (Meteorological Office 1969), the purpose of routine visibility measurements is to record the atmospheric 'turbidity'* at the surface. The Meteorological Optical Range (MOR) is given by World Meteorological Organization recommendations of 1957 as a quantity identical for practical purposes with visibility and defined as the length of path in the atmosphere required to reduce the luminous flux in a collimated beam of light to 0.05 of its original value. The light is defined as that emanating from an incandescent lamp at a colour temperature of 2700 K (World Meteorological Organization 1971).

The equivalence between visibility and MOR is based upon Koschmieder's theory (Middleton 1952) which states that:

$$C = e^{-\sigma d} \qquad \ldots(1)$$

where C is the contrast $= \dfrac{B - B_h}{B_h}$,

B = luminance of a black target viewed at a distance d,

B_h = luminance of the background around the target,

and σ = extinction coefficient.

The threshold value of C at which the target can only just be seen is taken to be 0.05. Therefore, in equation (1) with $C = 0.05$, d becomes the maximum range at which the target is seen, that is the visibility, V, hence

$$V = \frac{1}{\sigma} \cdot \log_e \frac{1}{0.05} \approx \frac{3.00}{\sigma}. \qquad \ldots(2)$$

Koschmieder's theory applies to a homogeneous atmosphere and the threshold value of C is that recommended by WMO (1971). Middleton's (1952) book describes in real situations the problem associated with determining the maximum range at which targets can be observed. Middleton also explains why Koschmieder's theory uses the extinction coefficient rather than the scattering coefficient. (In the *Meteorological Glossary* (Meteorological Office 1972) Koschmieder's theory is expressed in terms of the scattering coefficient.) If equation (2) is valid for real observations then the meteorological optical range is identical to the visibility because:

$$F = F_0 e^{-\sigma d} \qquad \ldots(3)$$

* The word 'transparency' used elsewhere in the reference seems to be more exact.

where F_o is the luminous flux in a collimated beam and F is the luminous flux measured at a distance d. The extinction coefficient is given by

$$\sigma = \beta + \alpha, \qquad \ldots(4)$$

where β is the scattering coefficient and α is the absorption coefficient.

The measurement of MOR, M, with a transmissometer of base length d_o is given by the equations:

$$\log_e \frac{F}{F_o} = -\sigma d_o,$$

$$\text{and } \log_e 0.05 = -\sigma M,$$

$$\therefore M \approx \frac{-3.00 d_o}{\log_e F/F_o}. \qquad \ldots(5)$$

If the luminous flux is measured with a suitably filtered photo-electric cell such that the voltage output by the system and its interface (assumed to respond linearly with luminous flux) is V_{TO} when $F=0$, V_{TM} when $F=F_o$ and V_T at an intermediate value of F, then equation (5) becomes:

$$M \approx \frac{-3.00 d_o}{\log_e \left(\dfrac{V_T - V_{TO}}{V_{TM} - V_{TO}} \right)} \qquad \ldots(6)$$

and this equation forms the basis of the operation of optical transmissometers.

With certain assumptions the MOR can be measured with devices which record scattered light. There are three basic types:

(a) the forward-scatter instrument,

(b) the back-scatter instrument, and

(c) the integrating nephelometer.

In this report results from a forward-scatter instrument (Plessey PVM) and an integrating nephelometer (M.R.I. Fog Visiometer) are presented. Although these are new instruments the techniques are not new and very similar devices are described in the *Handbook of Meteorological Instruments* (1956b).

An integrating nephelometer measures the scattering coefficient, β. Because of practical limitations the M.R.1. measures the integrated scatter from about 8° to 170° and therefore there is a truncation error (see Fitzgerald 1977). The MOR is then calculated as in equation (2) by assuming the absorption coefficient is negligible, thus

$$M \approx 3.00/\beta. \qquad \ldots(7)$$

For a model of strongly absorbing carbon aerosol, Twitty and Weinman (1971) suggest that the absorption coefficient can be as large as β although some recent measurements by Foot (1979) of smoke-contaminated air suggests that β is very much larger than α.

The angular pattern of scattered light from aerosols is a function of their complex refractive index, their size distribution and shapes. If we assume that there is no absorption and that there is no multiple scattering then for a particular wavelength, refractive index and size and shape distribution of aerosol particles, the extinction coefficent will be proportional to the light scattered in a fixed solid angle. At angles

between about $30° - 40°$ from the forward direction the sensitivity of this relationship to different distributions of particle size (in the ranges of hazes and fogs) is small compared with other directions. For the Plessey PVM, Winstanley and Adams (1975) estimate the error due to different distributions to be typically less than 12 per cent. If the output voltage from the PVM is equal to V_S, and V_{SO} is the value when there is no scattered light and $V_S - V_{SO}$ is proportional to the amount of scattered light then with the above assumptions equation (2) becomes:

$$M \approx \frac{3.00\,K}{V_S - V_{SO}} \qquad \ldots(8)$$

where K is a constant determined empirically.

Equations (6), (7) and (8) are used to determine the MOR for the transmissometers, the integrating nephelometer and the forward-scatter instruments. From now on the MOR thus calculated will be called 'visibility' with the explicit assumptions stated above.

For instruments such as the Marconi transmissometer and the Plessey PVM which use red or infra-red sources, there is an additional assumption not covered so far. It has been assumed that the wavelength dependence of these instruments is invariant for the different types of aerosols. Such a fixed difference is accounted for by the optimization of the values of d_o and K in equations (6) and (8).

3. THE INSTRUMENTS

The principal features of each of the visibility instruments used in this work are briefly discussed below and are summarized in Table I.

3.1. *The Mk 4 transmissometer*

A Mk 4 transmissometer consists of a projector which contains a 200 W tungsten-halogen source underrun by some 15 per cent from a stabilized d.c. supply. The light is concentrated with a parabolic mirror to an unfocused beam at the receiver 200 m away. The receiver ideally faces south so that it is least affected by sunlight incident on the background within its field of view. The receiver consists of a telescope and a selenium photocell whose response is weighted to that of the human eye. Heaters are provided to prevent misting of the optical surfaces and both the transmitter and receiver units have optical baffle tubes. In the Mk 4 system at Beaufort Park the output from the photocell is amplified and both unsmoothed and exponentially smoothed outputs are available. The exponential time-constant is 40 s.

The standard method of calibration is described in a 'Met O 16 Instruction' (Meteorological Office 1971). It involves setting the output of the amplifier equal to zero when the receiver is obscured, and then adjusting the gain of the amplifier so that the output is equivalent to the observed visibility when the obscuration is removed (see equation (6)). This procedure should be carried out with the visibility greater than 10 km.

TABLE I. *Summary of the details of the visibility instruments*

Instrument	Mk 4 Transmissometer	Erwin Sick SM 414 (loaned to Met. Office)	Marconi MET 1	Plessey PVM	M.R.I. Fog Visiometer 1580 (loaned to Met. Office)
Type of measurement	Transmission	Transmission (folded 4 times)	Transmission (folded twice)	Forward scatter 34°	Integrating nephelometer 8° – 170°
Sample size, base length or scattering volume	200 m base length inclusive of collimator tubes of dia. 150 mm	3 m base length + 1.5 m baffle tubes of dia. 105 mm	2 m base length + 0.6 m baffle tubes of dia. 50 mm	≈2 cm^3	≈100 cm^3
Relative degree to which sample is NOT enclosed	Excellent	Good	Good	Poor	Fair
Power consumption	≈500 W	≈35 W	≈20 W (Mean)	3 W (Mean)	50 W (Max.)
Max. dimension	205 m	5 m	3 m	0.3 m	1 m
Weight	> 100 kg	> 100 kg	63 kg	6 kg	20 kg
Output	Analogue 0 – 10 V	Analogue current converted to 0 – 2 V for trial	10-bit digital	Analogue 0 – 5 V (Trial versions)	Analogue 0 – 5 V
Time-constant *used* in trial	40 s	1 s	40 s	30 s	30 s
Source and modulation	Tungsten-halogen underun by 15%, no modulation	Quartz-halogen, lamp modulated mechanically	LED modulated at 1 kHz (wavelength 0.67 μm)	LED modulated at 125 Hz (wavelength 0.9 μm)	Xenon flash tube

Height used in trial	3 m	1.2 m	1.2 m	1.8 m	1.2 m
Period of analysis	Throughout experiments. Compared against observers from 20/10/75 to 29/2/76	12/10/76 to 20/1/77	7/2/77 to 6/5/77	12/10/76 to 20/1/77 Rain 'funnel' tests 1/10/77 to 31/3/78	10/2/77 to 6/5/77
Compensation features	None	1. Lamp output controlled automatically. 2. Mirror moved in hourly to give negligible atmospheric path. This signal can be used to compensate for the accumulation of dirt on the lens.	1. A mirror moved into the optical path at approximately 10 min intervals allows automatic compensation of the lamp output. 2. At 3-daily intervals V_{TM} is assumed to have decreased by 1 bit by contamination of reflector. If at any time V_T exceeds V_{TM} then 1 bit is added to V_{TM}. (1 bit $\widehat{=}$ 14 km visibility)	Output from LED continually used to reference its level to a constant value.	1. Output of the flash monitored and used to reference its level to a constant value. 2. An additional remote calibration check is available on the scale and zero.

3.2. *The Erwin Sick SM 414*

This is a transmissometer with a fundamental base length of 3 m. The transmitter and receiver are mounted in a single unit at one end of the optical path and a retroreflector at the other end. Both the transmitter/receiver and the retroreflector are shielded by optical baffle tubes 105 mm in diameter and 0.75 m long (see Figure 1(a)). The light beam is reflected at the far end of the optical path and to improve the sensitivity of the device the beam is folded as shown in Figure 1(a) so that the total geometrical length traversed by the light is about 18 m. The optical surfaces are heated to prevent the formation upon them of condensation which would attenuate the transmitted light and cause significant errors. The light source is a quartz-halogen lamp, the output from which is mechanically chopped to produce an alternating signal. By the use of phase-sensitive detection, the effects of stray light and amplifier drift are reduced.

Two other compensation features are incorporated. A second rotating chopper with a single reflecting segment is mounted so that the light is regularly returned directly to the detector without having traversed the atmospheric path. This signal is used to check the source level and the detector efficiency and these are automatically adjusted if they change. A further reflector is automatically placed in the light path about once per hour. This returns the beam through the lens system without any significant atmospheric traverse and the resulting signal is used to compensate for the effects of contamination on the lens surfaces by making changes in V_{TM} (see section 2) pro rata with changes in this reference signal.

Calibration of the instrument is performed by setting the output to the equivalent of the observed visibility on a particular occasion. In the present work, calibration was performed retrospectively by noting the mean output of the Sick for occasions when the Mk 4 transmissometer indication was greater than 12 km and then using this mean output for V_{TM}.

An uncompensated feature of this device is that, because of inadequate ventilation, the turbidity of the optical path in the baffle tubes is not necessarily the same as that in the free air between them. The time-constant of the device was 1 s.

3.3. *The Marconi MET 1*

This is also a retroreflecting, beam-folded transmissometer and the optical arrangement for it is shown in Figure 1(b). The concepts are very similar to the Sick SM 414 with a similar optical baffle system and a modulated light source. The differences are that the light beam makes only two passes and has a total geometrical path length of 5.2 m, the source is an electrically modulated LED (light-emitting diode) emitting in the visible red and the signal is handled digitally. The memory boards used in the logic system are battery supported. The time-constant of the device was 40 s.

The signal is digitized into 1024 bits so that 1 bit represents a change of transmission of about 0.1 per cent. Two methods of compensation are used. A mirror is moved automatically into the optical path at about 10 min intervals to reflect the source output directly back to the detector. Changes in the level of this signal automatically give rise to changes in the gain of the analogue to digital converter thus compensating for the effects of ageing in the LED and contamination on the front lens. At intervals of three days the

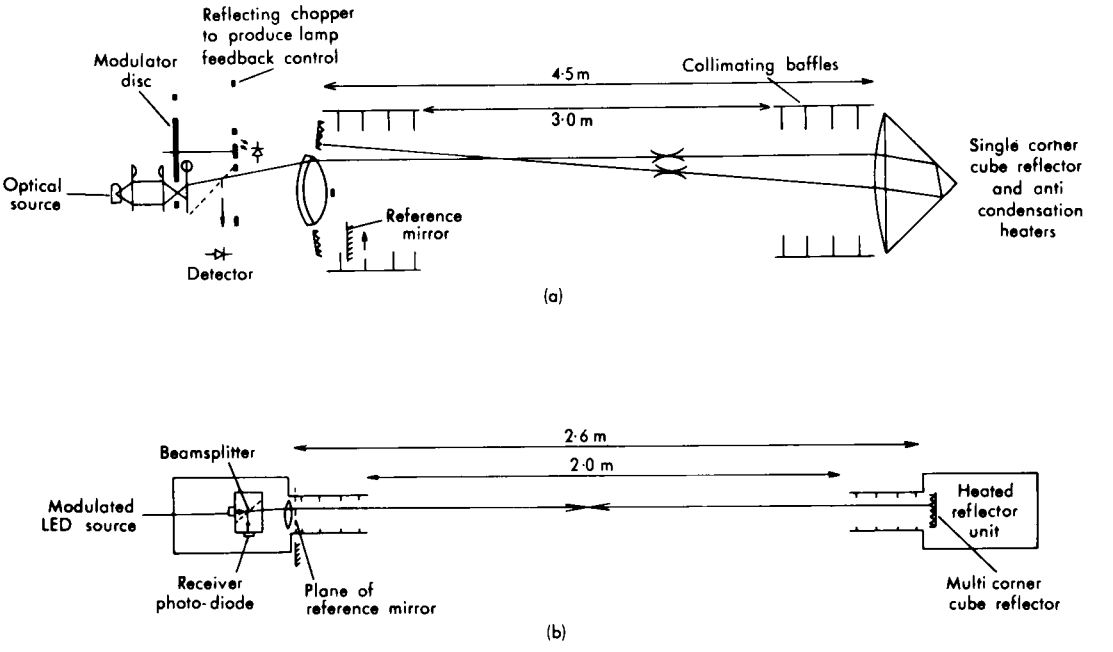

FIGURE 1. Principle of the optics on transmissometers
(a) The Erwin Sick (4 pass) transmissometer
(b) The Marconi MET 1 (2 pass) transmissometer

signal, V_T, is assumed to have decreased by one bit due to contamination of the retro-reflector. One bit is therefore added to V_T. If at any time $V_T > V_{TM}$, then single bits are subtracted until $V_T = V_{TM}$. This system of compensation assumes that the visibility is never low for long periods of time. If the instrument was installed at a site where the visibility never rose above 5 km then it would set itself up so that 5 km was measured as 14 km (which is the equivalent of the least significant bit) or infinity. A valuable feature of this instrument was the provision of three status flags which indicated that the instrument was operating in a calibration mode, that the battery support for the calibration memory was satisfactory and that the calibration compensation had not reached the limit of its dynamic range.

As with all transmissometers, the Marconi has the advantage that it fails 'safe', i.e. any failure is towards a poor visibility indication.

3.4. *The Plessey Point Visibility Meter*

There are two versions of this device: the early version (now obsolete) had a maximum range of 1.5 km, the present version has a maximum range of 5 km. Both instruments used in this work were 5 km versions. The equipment is shown schematically in Figure 2. It consists of an annular case 290 mm in diameter in which are housed an electrically modulated LED source emitting in the near infra-red and a detector system that views the 40 mm diameter central portion of the annulus volume at an angle of 34° to the transmitter beam path. The transmitter and the two detectors incorporate heated lenses.

The transmitted beam passes directly into a detector (1) (see Figure 2) which acts as a reference and the output from which is used to provide compensation for the LED drive and thus counter the effects of ageing and contamination in the transmitter. The second detector (2) looks directly at a light trap so as to reduce background noise. The signal acquired is that portion of the transmitted beam which is scattered forward at an angle of 34° by the aerosol in the 2 cm^3 volume that is common to the transmitter and receiver fields of view. This signal will be related to the visibility. The time-constant of the device that was used for this part of the work was 30 s. Wind-tunnel tests reported by Winstanley and Adams (1975) showed that for external airflows in the range 0.5 to 20 kn, the ventilation rate through the aperture was always greater than 50 per cent of the external flow.

A 'calibration block' which consists of a homogeneous suspension of aerosol set in a clear plastic resin can be used to check that the gain of the system has not changed. Such a check can be carried out during routine service operations. The function of the PVM is adversely affected by rain or snow (see section 5.4.4) and a rain funnel can be fitted to prevent water which collects on the instrument case dripping into the scattering volume. This modification is shown schematically in Figure 3 and is discussed further in section 5.4.4.

A practical disadvantage of this instrument is that it does not fail 'safe'. Any failure will result in a low or zero output voltage which is equivalent to a high visibility and is therefore a non-safe failure.

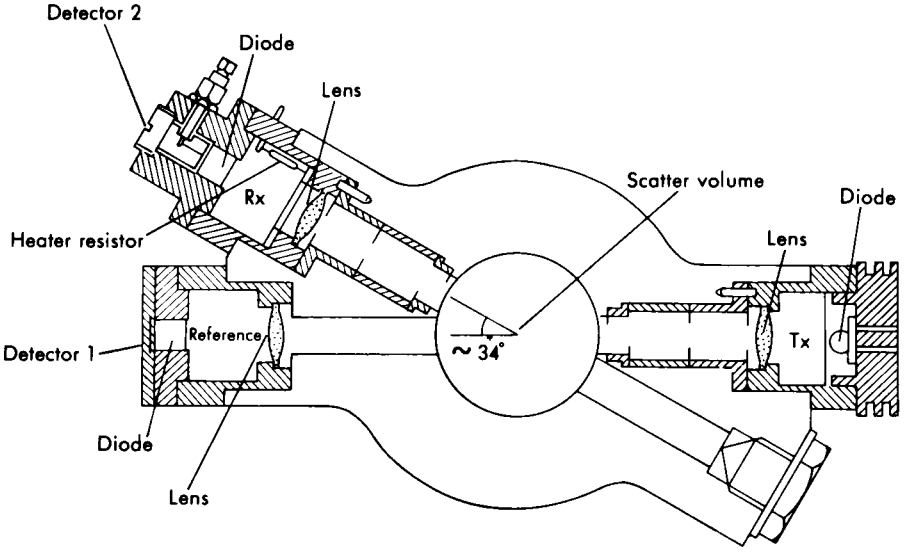

FIGURE 2. The optical system for the point visibility meter (PVM)

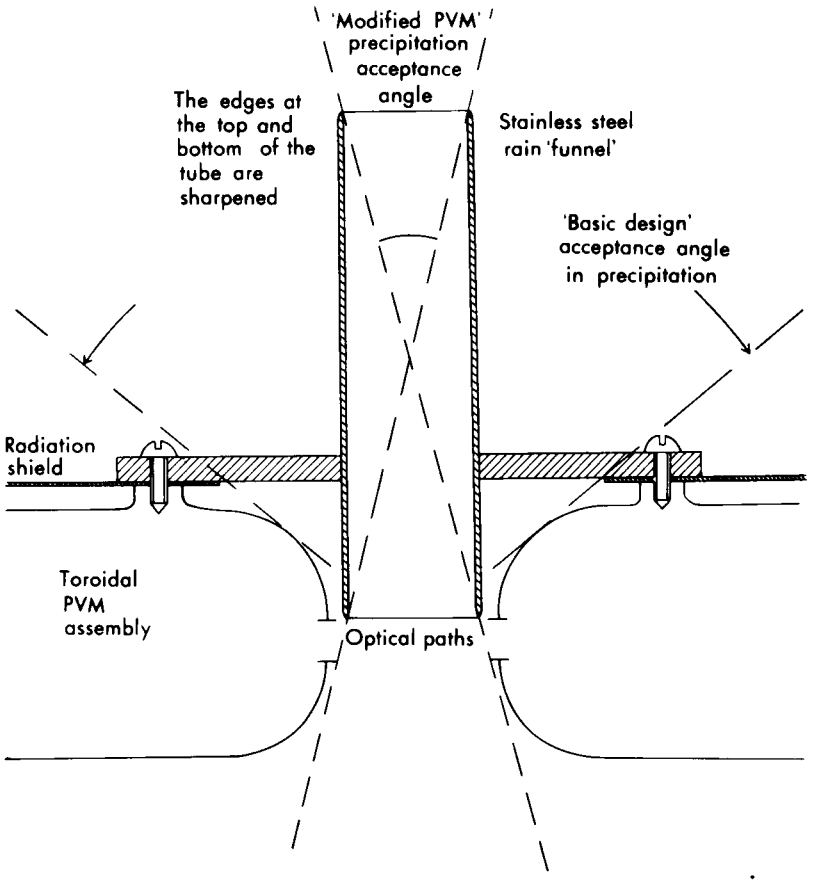

FIGURE 3. The rain-funnel modification to the PVM (approximately half-scale)

3.5. *The M.R.I. Fog Visiometer 1580*

This device is an integrating nephelometer which detects the light scattered by atmospheric aerosols into angles between 8° and 170° to the forward beam direction. The optical assembly consists of two sets of diaphragms installed inside two 4-inch diameter aluminium tubes which are permanently aligned facing each other. A photomultiplier tube located in one end of the assembly looks through the open centre section into a light trap at the opposite end. A xenon flashlamp illuminates the atmosphere in the open section through an opal diffusion glass and the scattering from a portion of this region is measured by the photomultiplier. The actual sample volume (about 100 cm^3) is defined by a series of collimating diaphragms in the two tubes and by the location of the opal glass. All internal surfaces in the optical assembly are coated with an optical black, non-reflective finish.

To match more closely the response of the optical system to that of the eye, a Wratten 2A filter is placed on the face of the photomultiplier tube to decrease the ultraviolet sensitivity. An automatic gain-control circuit requires direct observation of the flash, which is

accomplished by a reference photodiode mounted in a collimating tube in the optical assembly.

An air pump, mounted in the box at the light-trap end, filters and heats the ambient air and then pumps it down an insulated hose to the photomultiplier optical assembly. Thus clean warm air continually flushes this assembly to prevent condensation and to reduce dust deposition.

The Fog Visiometer can be calibrated, by the use of an internal calibration system, in all visibility conditions. The calibration system consists of two solenoid-actuated assemblies, one for setting the system zero (corresponding to no atmospheric obscuration) and the other for setting a predetermined level of scattering.

The zero calibrator consists simply of a black shutter which blocks off the hole in one of the collimating diaphragms, thereby preventing any scattered light from the flash from reaching the photomultiplier tube. This no-scattering condition simulates the conditions encountered in clean air when the scattering from the atmosphere is very small.

The other calibrator consists of a set of diffuse reflecting surfaces which can be positioned in front of a collimating diaphragm in such a way as to receive light directly from the flash and to scatter a portion of this light toward the photomultiplier tube. These reflectors, which are coated with a high-stability white surface, are calibrated at the factory. At the same time as it scatters a calibrated amount of light into the photomultiplier, the calibrator also blocks any of the scattered atmospheric light from reaching the photomultiplier; thus its operation is independent of the ambient visibility conditions. (There is a small effect due to the scattering of light in bright fog, but the error involved in ignoring this is small and within the accuracy limitations of the instrument.) The time-constant of the device was 30 s.

4. EXPERIMENTAL ARRANGEMENTS AND PROCEDURES

4.1. *Site details and method*

A plan of the positions of the instruments used in this study is shown in Figure 4. It was not possible to expose all the instruments at the same height, a fact that was of importance in assessing some of the results of fog studies reported in section 6. The heights of the optical axes of the instruments are listed in Table I. Data from wet- and dry-bulb electrical resistance thermometers in the Stevenson screen and from a Porton anemometer and wind vane, all on the visibility site, were used together with data from a tipping-bucket rain-gauge on the adjacent rain-gauge site. The daily registers kept by the observers in the CRDF (cathode-ray direction-finder) building were referred to for additional information.

The initial data used for the comparison of the Mk 4 transmissometer with the observers' estimates of visibility were taken from Kent recorder charts and from forms completed by the observers who did not have access to the transmissometer output. The data for the other intercomparisons were all collected on an automatic data logger. The sensors were interrogated at 30-minute intervals except when the visibility as indicated by the Mk 4 transmissometer was less than 1 km when the interval between readings was reduced to 5 minutes.

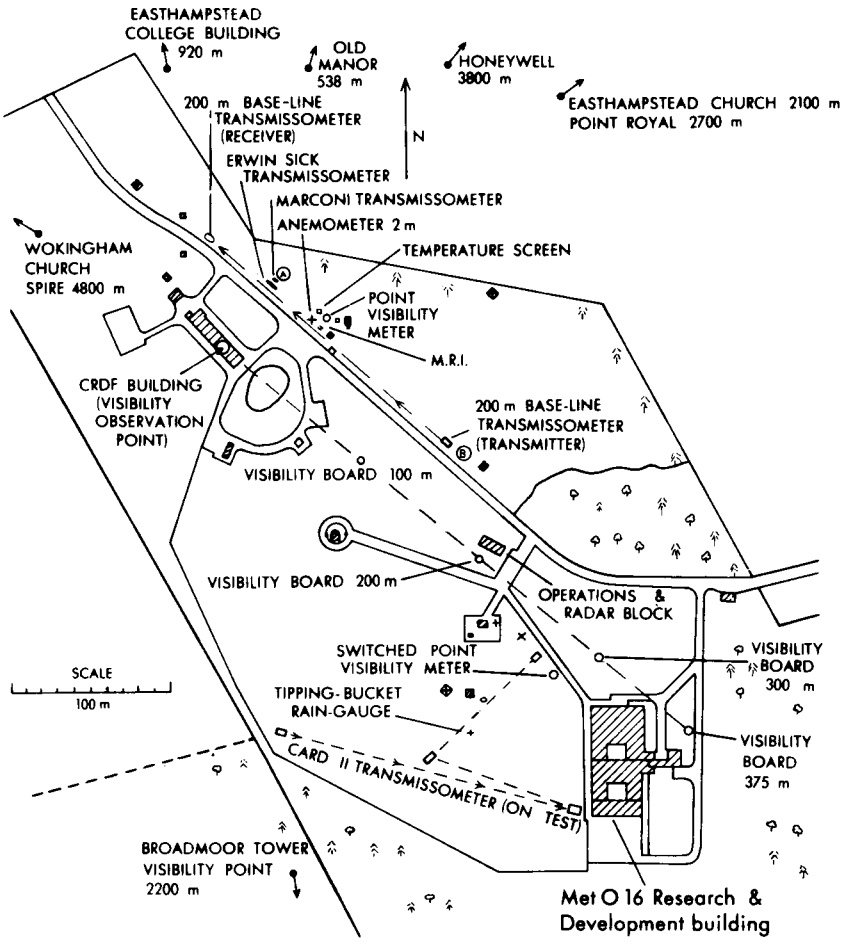

FIGURE 4. Site plan of Beaufort Park showing the location of the instruments

All visibility points are referenced from the CRDF building, 75 m above mean sea level. Circled letters A and B indicate siting of some instruments (see section 6).

The calibration of the Mk 4 transmissometer was carried out in accordance with the procedures given in the official instructions (Meteorological Office 1971) except that calibrations could not be performed as frequently as every 10 days and an additional d.c. amplifier in this particular Mk 4 (the Mk 4C) was zeroed with the receiver obscured.

The other instruments were installed and maintained as recommended by the various manufacturers. Every weekday morning the outputs from the devices were inspected to determine whether there were any obvious faults in the systems. This check revealed problems with spiders on the PVM, the Marconi and the M.R.I. The Erwin Sick transmissometer suffered to a lesser extent from this problem possibly because the aperture of the optical system was larger than in the other devices. The creatures spin webs across the optical paths thus seriously affecting the output of the instruments. This problem was particularly severe with the PVM for three reasons. The physical size of the PVM aperture is less than that of the other devices and seems particularly agreeable to

spiders. Furthermore, the PVM indicates increasing visibility by a decreasing voltage and has a valid output of 0 V. Obscuration by spiders' webs causes a 0 V output that cannot be distinguished from very good visibility. This prevents the use in the PVM of electronic flags for indicating that the system has been affected by serious obscuration which is a feature of the MET 1 made possible by the fact that it uses decreasing voltage to indicate decreasing visibility and 0 V is not a valid output. This deficiency could be a significant drawback to the usefulness of the PVM on unattended sites. Attempts to repel the spiders by the use of various noxious creams all failed after only a week or so.

Special subsidiary experiments were carried out to study the sampling problems of the PVM and the problems which arise with single pole visibility devices as a result of the spatial inhomogeneity of fog. These experiments are separately described in sections 5.4.5 and 6.

4.2. *Methods of analysis*

The data analyses were designed with a view to illustrating how well the instruments performed in principle, with what certainty the output from the instruments could be accepted in an operational situation and how the accuracy of the output varied with visibility. The effects of attempts to optimize the various instrument constants used in the analysis of each type of output were also studied as was the performance of each instrument in rain and drizzle. For all the statistical analyses visibility data were restricted to the range 100 m to 5 km. 100 m represents the lower limit of resolution of the Mk 4 transmissometer and 5 km represents the maximum usable range of the output from the new devices.

4.2.1. *Analysis A—homogeneous conditions data*

To study the intrinsic capability of the instruments, the analysis was confined to occasions when the complication of atmospheric variability was at a minimum. These were occasions of well-mixed fogs and hazes when inhomogeneity around the site was unlikely. Further, to yield the best performance of which the instruments were capable, the instrumental constants were optimized by reference to linear regressions performed on data in the range 100 m to 1 km.

The criteria used to decide whether the conditions of 'well-mixed fog or haze' actually prevailed were:

(a) The mean rate of change of the visibility indicated by the Mk 4 transmissometer was less than 1 per cent per minute (defined as less than 5 per cent between 5 min readings or less than 30 per cent between 30 min readings).

(b) Wind speed more than 3 kn.

(c) No tips of the tipping-bucket rain-gauge in the previous 1½ hours.

(d) Data obtained for periods for which entries in the Daily Register indicated the presence of snow or freezing precipitation were not included.

(e) For the PVM comparison, data were restricted to those obtained when the temperature was above freezing because of possible changes in particle types in freezing fog.

On occasions of rapidly varying fogs, it was possible to find two consecutive spot readings which did not fail criterion (a). Therefore, after an initial computer analysis, it was necessary to go through the accepted data to reject any consecutive points which showed poor agreement and were clearly part of an occasion of rapidly changing visibility. The number of points thus rejected was less than ten for any of the comparisons. The data were treated in two ways. First, an overall comparison between the data from the new instruments and those from the Mk 4 was made in the form of a scatter plot which should show up any significant non-linearities or offsets. Second, to assess the intrinsic accuracy of the visibility measurement made by each device when compared with that of the Mk 4 transmissometer, the well-mixed fog and haze data were divided into those sets defined by the visibility bands 100 – 200 m, 900 – 1100 m and 2900 – 3100 m as indicated by the Mk 4. (In the comparison with the Marconi, the top band was chosen as 2700 – 3500 m in order just to include two of the digitized output values of the instrument.)

4.2.2. *Analysis B—operational conditions, all data*

In operation, very few restrictions can be placed upon the external conditions which must prevail before the output of a visibility measurement device is useful, and it is therefore important to establish the certainty which can be attached to the output in all prevailing conditions. To examine this question, the output from the new instruments was compared against that of the Mk 4 for all occasions for which the visibility given by the Mk 4 was in the range from 100 m to 5 km inclusive. Furthermore, since in an operational situation it would not normally be possible to optimize the instrumental constants, the manufacturer's quoted values of the constants or values estimated from his own calibration data were used. As in the case of the homogeneous data of Analysis A, the results are presented first as a scatter plot and then those data in the visibility bands 100 – 200 m, 900 – 1100 m and 2900 – 3100 m (2700 – 3500 m for the Marconi) were recomputed, this time by the use of the optimized instrument constants, and compared with the equivalent Mk 4 data for accuracy.

4.2.3. *Analysis C—rain conditions data*

It is of particular interest to consider the performance of the instruments in rain and drizzle. If it can be shown that the inclusion of occasions of rain seriously degrades an otherwise sound performance, then steps can be taken to exclude such occasions as invalid during operational use. For this purpose, an occasion of rain or drizzle was defined by:

(a) At least one tip of the tipping-bucket rain-gauge in the previous 1½ hours.

(b) No snow or freezing precipitation indicated in the Daily Register.

As in the previous two analyses a scatter plot and an accuracy check were performed for each of the transmissometers. There are good physical grounds for believing that the scattering instruments will not perform well in rain. Data obtained with these devices in rain were therefore separately identified and have been treated as described in sections 5.4.4 and 5.5.2. The constants used were the optimized values derived for Analysis A.

TABLE II. *Summary of the results of previous work on the Mk 2 and Mk 3 transmissometers*

	Heathrow 1965/66 (Night) Mk 2 – Gold Meter			Heathrow 1965/66 (Daytime) Mk 2 – Observer			Leeming 1971/72 (Night) Mk 3 – Gold Meter			Scampton 1971/72 (Night) Mk 3 – Gold Meter			Abbotsinch 1971 (Night) Mk 3 – Observer			Heathrow 1971/72 (Night) Mk 3 – Observer		
Range of visibility Gold Meter or observer *metres*	*d*	*s*	*n*	*d*	*s*	*n*	*d*	*s*	*n*	*d*	*s*	*n*	*d*	*s*	*n*	*d*	*s*	*n*
100 – 1000	1%	20%	12	0%	11%	12	4%	14%	73	– 18%	65%	71	– 17%	58%	71	– 9%	33%	348
1100 – 2000	0%	30%	48				1%	13%	78	3%	54%	96	– 7%	39%	28	– 15%	16%	519
2100 – 3000	0%	30%	100	0%	27%	41	0%	15%	45	12%	69%	10	– 18%	13%	239	– 19%	15%	431
3100 – 4000							– 1%	19%	64	41%	15%	13	– 11%	16%	318	– 21%	14%	319
4100 – 5000							– 2%	24%	26	– 58%	13%	6	– 8%	20%	339	– 25%	18%	343
5100 – 6000							0%	10%	41	– 38%	32%	8	– 15%	16%	232	– 22%	15%	253
7100 – 8000							– 3%	5%	8	– 60%	–	2	– 7%	17%	234	– 27%	16%	274
Comments	Results optimized by assuming 7% degradation of transmitted beam.									Questions were raised as to siting of this transmissometer			Gold Meter used only occasionally			Gold Meter used 50% of the time		

Mean (*d*) and standard deviation (*s*) of the differences in the two measurements of visibility expressed in terms of percentage of the visibility (*n* is the number of observations).

5. RESULTS

5.1. *The Mk 4 transmissometer*

5.1.1. *Previous work*

Table II brings together some previous work on Meteorological Office transmissometers. This work was done on the Meteorological Office Photo-electric Visibility Meter Mk 2, which was an earlier version of the transmissometer, and the Mk 3, which was renamed Mk 4 when recently accepted as an operational instrument. In some of these comparisons the transmissometer is judged against the visibility derived from the results of the Gold visibility meter which are strictly measurements of meteorological optical range (MOR) and also include unknown, and probably very variable, operator errors.

In results from London/Heathrow Airport it was found necessary to assume an arbitrary degradation of 7 per cent in the transmitted beam intensity of the transmissometer, but, given that assumption (fudge factor), the overall mean differences for both comparisons (i.e. with the Gold visibility meter and the observers) were very good. The comparison at Scampton was very poor and questions were raised about the siting of the transmissometers. However, even when the mean difference between the results of the two techniques for visibility determination was small, the variability was large, with standard deviations of the order of 15 to 30 per cent.

5.1.2. *Present comparisons*

5.1.2.1. *Calibration problems.* In previous comparisons between the Mk 4 transmissometer measurements and other visibility measurements very little attention seems to have been paid to the effects of calibration errors in the Mk 4 data. Such errors can arise either through an inadequate calibration procedure, or through drift of the output with time, or both. It is instructive to consider what will be the effect on measured visibilities of calibration errors of known size.

Figure 5(a) shows for both a transmissometer and a scattering instrument (the PVM) the effect of a calibration error, that is to say a change in the value of V_{TM} or K in equations (6) and (8), errors most likely to arise from the contamination of optical surfaces or from an uncorrected change in source intensity. The strong sensitivity of a transmissometer to a calibration error is clear from the figure. From equation (6) it can be seen that the ordinate of Figure 5(a) scales with the base length so that as the transmissometer base length is made shorter, so the effect of a calibration error increases. Some form of progressive compensation for changes of source intensity and surface contamination is therefore essential in short-base-length transmissometers. It can also be seen from the figure that scattering instruments are not sensitive to this effect and in this respect they therefore have an intrinsic advantage for use in locations where surface contamination is a serious problem, for example at sea.

Figure 5(b) illustrates the effect of a zero shift, that is a change in V_{TO} or V_{SO}. This can be caused by high background illumination or a drift in the instrument electronics. The problem can be reduced by the use of a modulated source and phase-sensitive detection methods and all the new instruments have these facilities. The Mk 4, however, relies on the stability of d.c. circuitry and is very susceptible to drift errors. During the experiments a change in zero level as large as 1.5 per cent of full scale was observed for the Mk 4. A

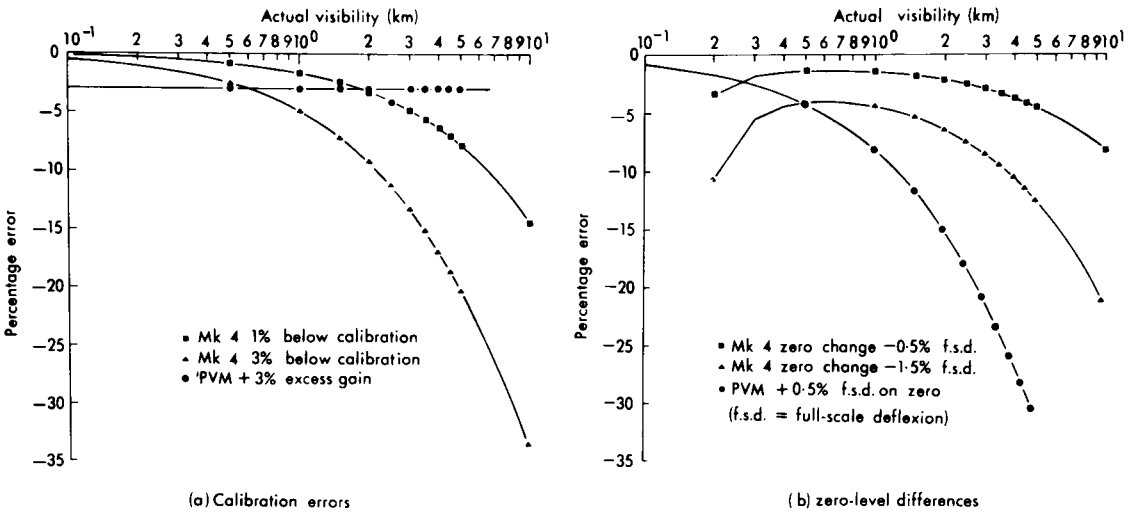

FIGURE 5. The effect of calibration errors on the Mk 4 transmissometer and the Plessey Point Visibility Meter

zero shift of 0.5 per cent of full scale which is shown in Figure 5(b) for the PVM is much larger than any such shift due to electrical drift that has been experienced, although spiders' webs can and do cause such large changes, and errors of this magnitude can be expected for a PVM that is not individually calibrated.

The drift actually experienced with the Mk 4 transmissometer over a 133-day period during which the instrument was calibrated twice is shown in Figure 6. The comparisons used in this figure were made for observer values of visibility of 10 km. It is shown below that this was an unfortunate choice of visibility at which to determine the actual value of the drift, but it nevertheless serves to illustrate the existence of the problem. The figure shows the ratio of the transmission measured by the Mk 4 to that calculated for a 200 m path from the observer's reported visibility value.

The transmission of the Mk 4 was taken to be V_T/V_{TM} on the assumption that V_{TO} remained zero after calibration. For a perfectly calibrated instrument the ratio of the transmissions should be unity, provided that the observer's estimate of visibility is not in error. The solid lines on the figure are regression lines for the periods between calibrations. The first period was not sufficiently long to provide a meaningful regression line and the mean of the data represents the best correction available for that period. The second period, however, shows a drift (i.e. a rate of change of V_{TM}) of 2 per cent per month while the third period shows a drift in V_{TM} of 1.5 per cent per month. These calculations were repeated for occasions when the observer's reported value of visibility was 15 km or greater and the results are shown in Figure 7. The same trends are evident, but the mean of the drift error over the whole period is 1.2 per cent lower than that obtained from Figure 6. This difference may have arisen from the assumptions made in the comparison of visibility and MOR, but it is thought more likely to be due to uncertainty in the observer's values of visibility because they had no visibility points at ranges greater than 5 km. It is shown in a later section that this gives rise to large rounding errors

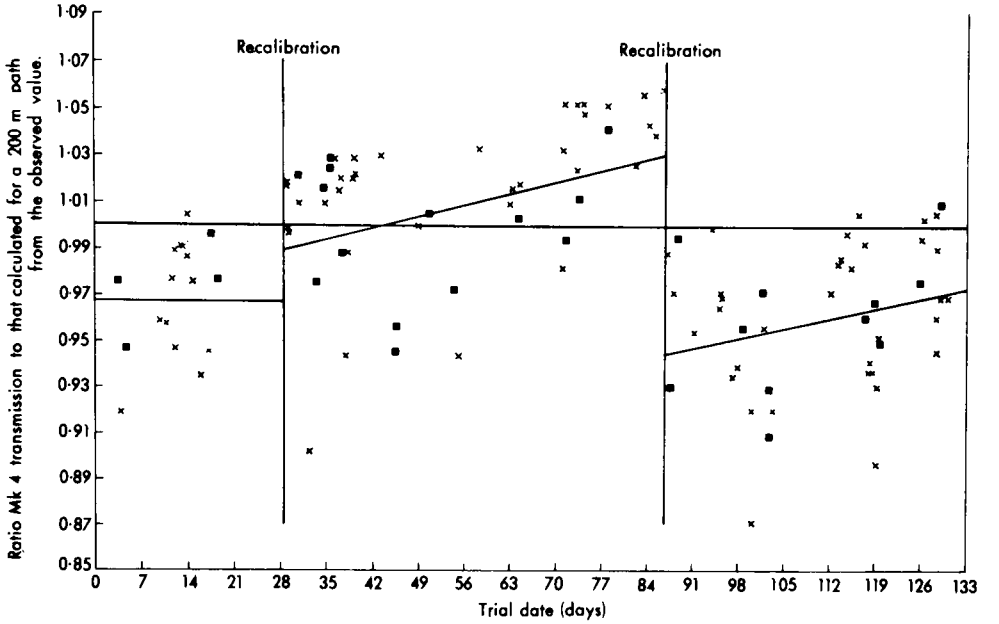

FIGURE 6. Drift of the Mk 4 transmissometer in the period 20/10/75 – 29/2/76, observed value of visibility 10 km

Mean ratio 0.984 ■ daylight observations x night-time observations

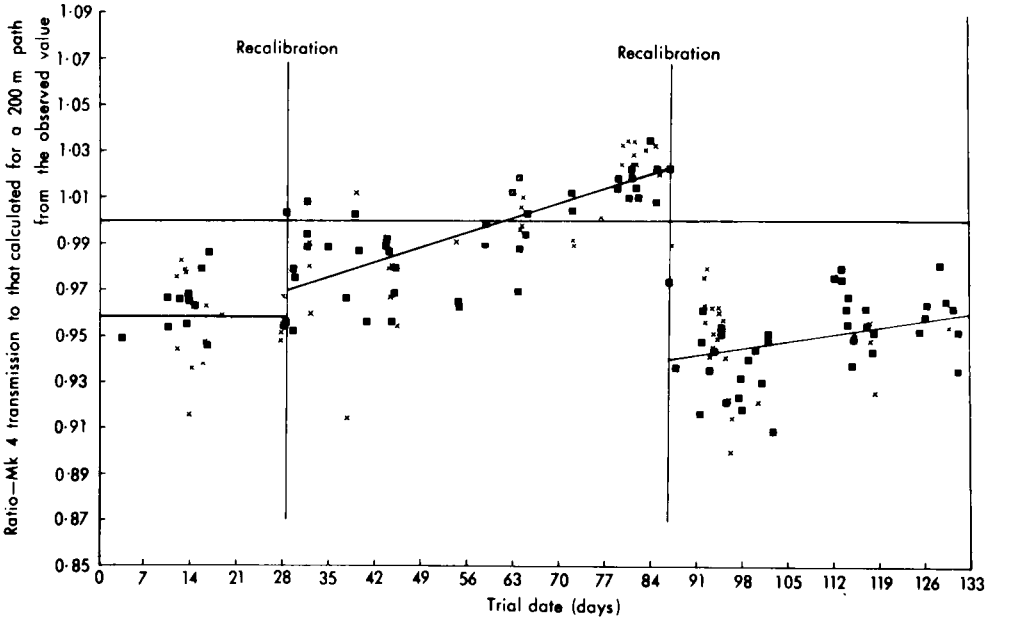

FIGURE 7. Drift of the Mk 4 transmissometer in the period 20/10/75 – 29/2/76, observed value of visibility 15 km

Mean ratio 0.972 ■ daylight observations x night-time observations

at high visibilities which will adversely affect actual calibrations of the Mk 4 and the calculations of drift errors. This difficulty was not realized until after all the corrections for drift had been applied to the results of the comparisons between instruments and these corrections were derived from data obtained when the observer's visibility was 10 km or more. To recompute these corrections would have been too great a task—particularly since the relative effects between instruments are likely to be small except at visibilities greater than 6 km. However, since the comparison of the Mk 4 with the observer is significantly distorted by the effect, especially at high visibilities, an attempt was made to establish a more accurate estimate of the drift error by recomputing it on the basis of observed visibilities in the band 3–6 km and the result of this is shown in Figure 8. Unfortunately there were insufficient data in this band to yield sensible regression lines from which the drift rates could be determined, but the mean offset over each period, deduced from these results, is likely to be less affected by uncertainties in the observer's value of visibility than those deduced from the 10 km or 15 km data sets. Therefore, the final correction to be applied to the data used for the comparison with the observer's values was obtained by combining the slope of the regression line from the 15 km data with the mean offset of the 3 – 6 km data. For the first period, up to day 28, no regression was possible on any of the data and the mean of the 3 – 6 km data was the best correction that could be devised. The lines shown in Figure 8 show these correction values.

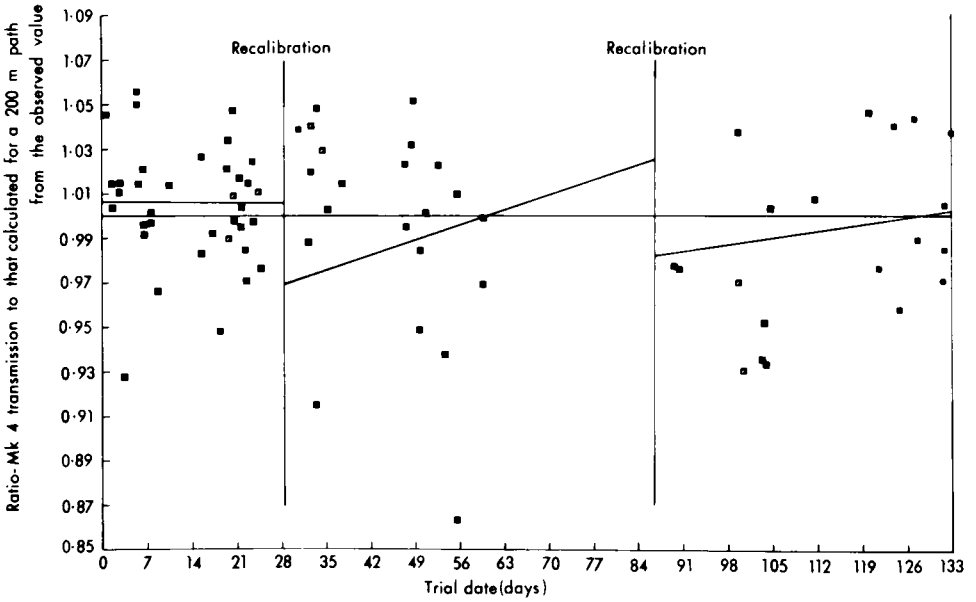

FIGURE 8. Drift of the Mk 4 transmissometer in the period 20/10/75 – 29/2/76, observed value of visibility 3 – 6 km

Mean ratio 1.000 ■ daylight observations

The technique used for making the correction was, of course, the same for both sets of corrections. The drift in V_{TM} was calculated for the periods between calibrations from the linear regressions of Figures 6 and 7 by writing V_{TM} in terms of the day of the trial D in the form

$$V_{TM} = V_{TM_0} + \gamma D, \qquad \ldots(9)$$

where γ is the rate of change of V_{TM}, and V_{TM_0} is the value of V_{TM} immediately after calibration when $D=0$. The largest value of γ computed on the basis of 10 km reported visibilities was -3 per cent per month. The effect of drift of this magnitude is shown in Figure 5.

A particularly interesting feature of Figures 6 and 7 is that for these results the agreement between the Mk 4 and the observer values of visibility was not generally improved after recalibration. In particular, it can be seen that the second calibration changed the error in V_{TM} from $+3.7$ per cent to -5.3 per cent. The present calibration procedure is an attempt to make the transmission given by the Mk 4 agree with the visibility at the time of the calibration and should, ideally, be carried out when the visibility is 10 km or more. There is therefore a prima-facie contradiction in that the act of calibration should apparently force the ordinate values of Figures 6 and 7 to unity. A detailed examination of the Mk 4 output in the 6 hours immediately following the second calibration indicated that the observer's values and those of the Mk 4 were in good general agreement for that period. This suggests that calibrations performed by a single point adjustment method are strongly influenced by subjective observer effects, especially where there is a lack of long-range visibility points.

To avoid this difficulty, or at least to mitigate its effect, the method of calibrating the Mk 4 transmissometer should be changed. A record should be kept of the difference between the observer's estimate of visibility and the Mk 4 output for a series of occasions when the visibility is 10 km or more. After a minimum of, say, 20 such differences have been obtained, their mean should be used to compute a correction to V_{TM} and the transmissometer should then be adjusted to incorporate this correction. At an unattended automatic weather station (AWS) such a procedure is not practicable; however, it would be possible to carry out a correction in the software in a similar manner to that used in the Marconi instrument (see section 3.3), provided that the site offers frequent occasions when the visibility is 15 km or more. If these conditions cannot be met, then the use of the standard Meteorological Office transmissometer on unattended AWS cannot be recommended.

5.1.2.2. *Comparison between the Mk 4 transmissometer and observers' values.* For this comparison, the total available data set was sifted to remove any member of the set which had been obtained in conditions of significant inhomogeneity around the site. For example, data from occasions when the observer could see a rain shower or similar visual discontinuity were excluded. The total amount of data so discarded was only 1 per cent of the set and the number of acceptable comparisons for observer visibilities less than 15 km was 1056.

Figure 9 shows the percentage frequency with which the observers reported visibilities up to 15 km; the daylight observations are indicated as a portion of the total. The figure also shows the visibility targets available to the observers and the abscissa is marked at

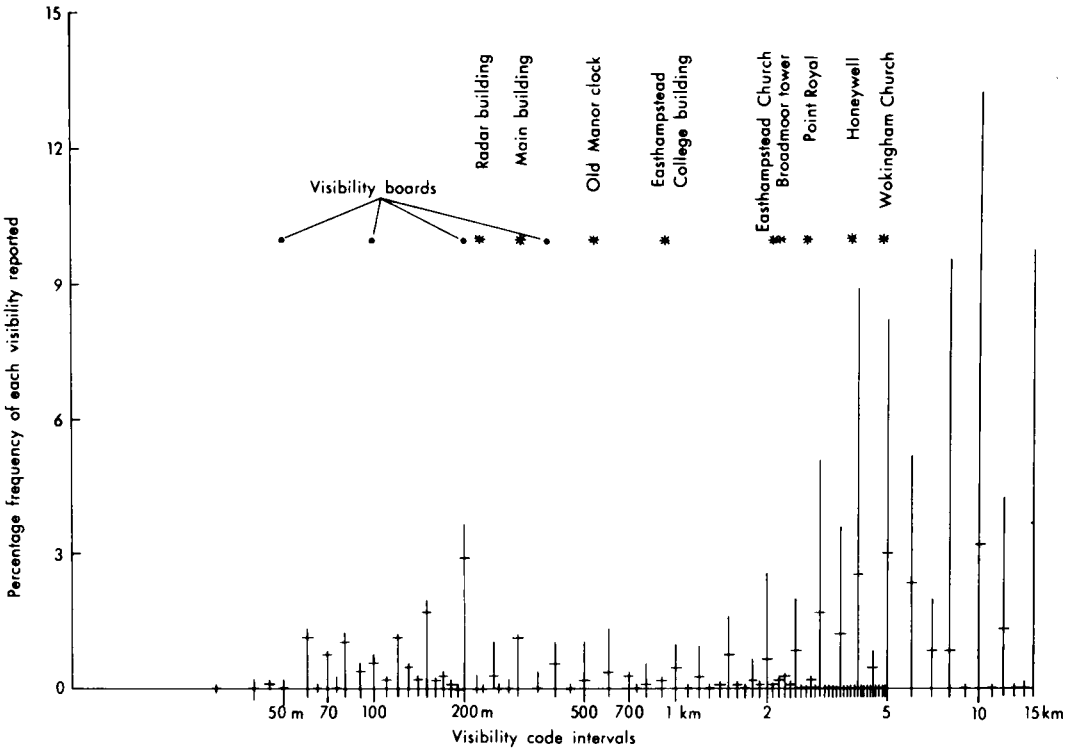

FIGURE 9. Percentage frequency of observers' visibility reports as a function of visibility
Daylight observations are a portion of the total (indicated by +)

standard SYNOP code intervals at which visibility is reported. Several features of this figure are worthy of particular comment. Firstly, there were no visibility targets at ranges beyond 5 km. Secondly, there are a number of SYNOP code levels that were never reported, notably the group from 3.1 to 3.4 km inclusive and the 9 and 11 km levels. Other groups of SYNOP code values were very rarely reported, e.g. 13 km, 14 km, values between 2.0 and 2.5 km and values between 1.0 and 1.5 km, except 1.2 km which is just beyond the defining limit for fog, and between 1.5 and 2.0 km. This strongly suggests that observers tended to round their observations to preferred integral or half-integral values. Thirdly, for values less than 450 m the observers recorded visibilities at a finer resolution than it is possible to report with the code. Fourthly, during the daytime the 8 km value was infrequently recorded compared to the night-time. Finally, the 10 km value is preferentially reported, especially at night. This suggests that at visibilities of 10 km or more the observer's resolution is effectively 2 – 2.5 km, that below but close to 10 km, especially at night, there is a tendency to report a lower visibility than 10 km, and that 8 km is arbitrarily chosen. These characteristics of the observers' reports are not surprising: any estimate of visibility greater than a few kilometres without the aid of visibility points and especially at night is not much better than guesswork, and most people have an innate preference for a resolution in units of two or five. Whilst these points may have very little significance to the value of reported observations, they bear heavily on the assessment of the performance of the Mk 4 transmissometer when judged

against that of the observer. This is especially true if the calibration of the instrument is carried out at an estimated visibility of 10 km and the high visibility comparisons are given equal weight with the low visibility comparisons when making the overall assessment.

Figure 10 shows the comparison between the Mk 4 transmissometer measurements and the observers' reported visibilities. The means and the standard deviations of the Mk 4 values are plotted against the observer values divided into the following bands: 100 – 199 m, 200 – 399 m, 400 – 599 m, 600 – 799 m, 800 – 999 m, 1000 – 1499 m, 1500 – 1999 m, 2000 – 2499 m, 2500 – 3499 m, 3500 – 4499 m, 4500 – 5499 m, 5500 – 6499 m, 6500 – 7499 m, 7500 – 8499 m, 8500 – 9499 m, and 9500 – 10 499 m. On the graphs the points have been plotted at the mean value of the data in each band. The standard deviations were calculated from the difference in the transmission measured by the Mk 4 and the transmission for a 200 m path derived from the observers' values of the visibility. These results were then used to calculate the positive and negative errors in visibility. The resulting positive and negative values will therefore not be equal. The corrections to the Mk 4 transmissions are those derived from the combination of drift and mean offset discussed above.

Figure 10(a) shows the uncorrected daylight observations and Figure 10(b) shows the same data after corrections have been applied. It is clear that the application of the corrections has improved the agreement between the Mk 4 and the observers at the higher visibilities (more than 6 km) but has had little effect at lower visibilities. The agreement between the mean of the Mk 4 output and the observed values is strikingly good throughout the range with the exceptions of the 600 – 799 m band and the 6 and 10 km points. For the 600 – 799 m band the departure from the 1:1 relationship with the Mk 4 is less than one standard deviation with only seven data points so that there are no grounds for believing that there is a particular problem at this visibility. The 6 and 10 km points both contain a relatively large amount of data but there are no visibility targets at these ranges and, having regard to the discussion of Figure 9 given above, it seems quite likely that the disagreements between the Mk 4 and the observers at these levels owe more to the observers' uncertainty than to the transmissometer.

Although the mean values given by the Mk 4 agree well with the mean value given by the observers, the variability in the results is quite large. It ranges for the daytime data from about + 28 per cent to – 25 per cent for visibilities up to 6 km but then becomes very large, especially in the positive direction. This variability is a combination of the uncertainties of both the Mk 4 and the observer and it is surely no coincidence that the large increase in variability begins at that visibility which corresponds to the furthest available visibility point for the observer. The smallest variability occurs around values of 1 km at which the transmissometer is expected to be at its best. At this level of visibility the variability is from about + 13 per cent to – 12 per cent for daytime values. At least some of this can still be attributed to the observer and some to the inhomogeneity of the atmosphere so that it is reasonable to conclude that a properly maintained and calibrated transmissometer with its output corrected for drift provides at least as good an indication of visibility as an observer for values of visibility up to 5 km in daytime conditions. It is very likely from the evidence given here that at larger visibilities up to 10 km it yields a better estimate of prevailing visibility than the observer, unless the observer happens to have available visibility points at these greater distances.

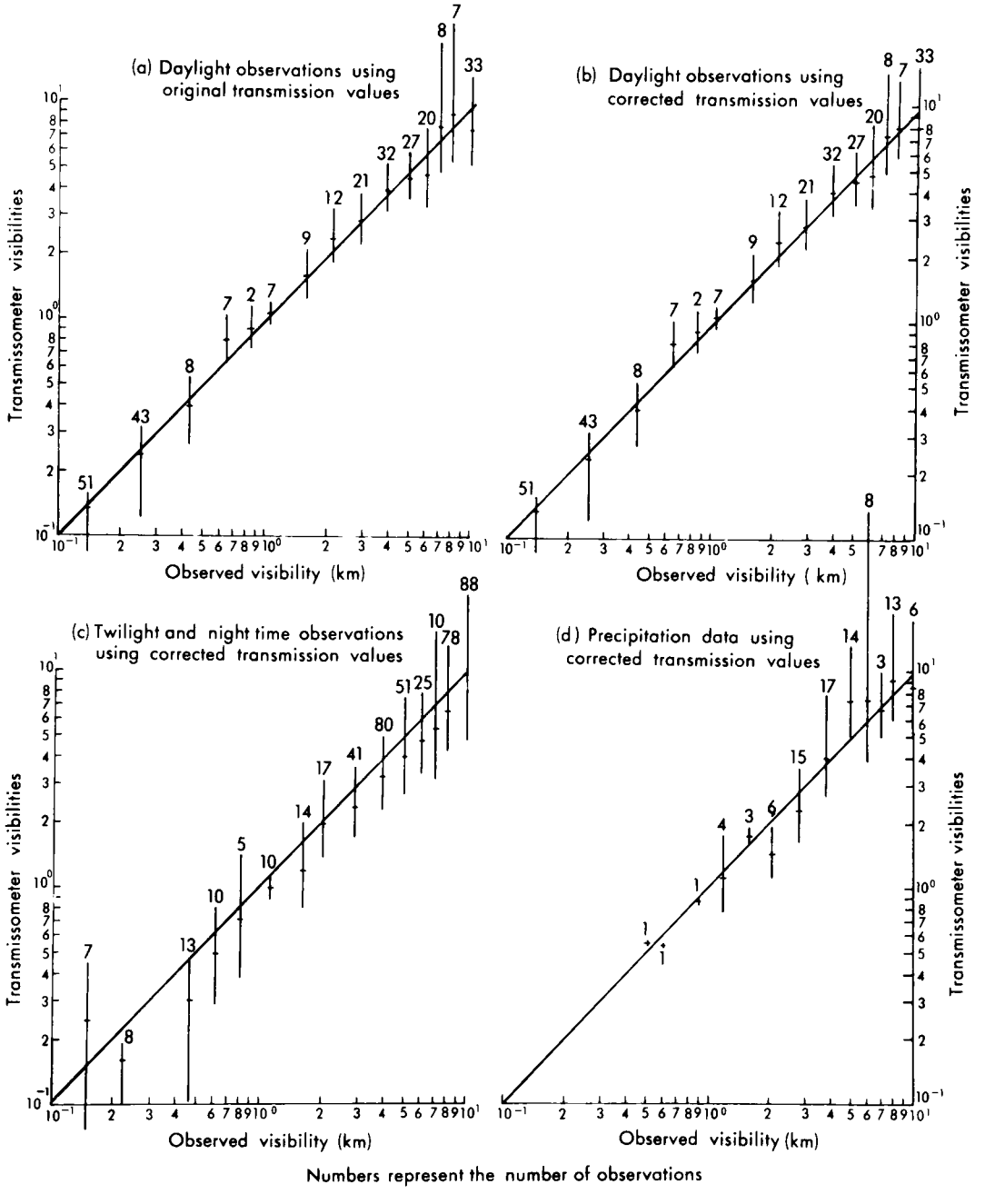

FIGURE 10. Comparison of observer-reported visibility with independently measured Mk 4 transmissometer visibility

The night-time observations are shown in Figure 10(c) and clearly both the mean agreement and the variability are much worse than for the daylight case. It is hard to imagine any physical reason why the transmissometer characteristics should change at sunset and therefore we might reasonably conclude that the deterioration in both the means and the standard deviations shown in Figure 10(c) is due to poorer estimates on the part of the observer. The discussion of Figure 9 showed clearly that the observer's performance does deteriorate at night relative to the day and we therefore conclude that the Mk 4 transmissometer can give a consistently better estimate of the night-time visibility than can an observer for all visibilities.

Figure 10(d) shows the comparison for rain data extracted from the total day and night sets. The number of observations is very small and it would be imprudent to draw any definite conclusions from them but there does not seem to be any reason to believe from this evidence that the conclusions drawn for the cases discussed above should be different for rain situations.

5.1.2.3. *Conclusions.* It is worth while drawing together in a summary the conclusions of this section. Firstly, we have shown that transmissometers are very susceptible to calibration and drift errors and that the present method of calibration for the Mk 4 transmissometer is inadequate if the instrument is to be used for visibilities greater than 5 km; an alternative scheme is suggested. Secondly, we have shown that a properly calibrated and maintained transmissometer can, after drift corrections have been applied to its output, yield visibility measurements that are as good as or better than estimates made by an observer during the day and better at night. These results do not apply to strongly inhomogeneous conditions such as local showers which may reduce visibility significantly over a narrow arc of horizon. Finally, we have shown that so far as our limited data can be considered typical, there is no evidence that there is a particular deterioration in the performance of the transmissometer in rain.

5.2. *The Erwin Sick SM 414*

5.2.1. *Instrumental considerations*

This device behaved reliably throughout the experiments. No significant drift of the response was detected and no problems with spiders or insects were experienced. Attempts to deform the structure manually did not affect the output from the instrument. In a one-hour period of moderate snow, with the wind blowing along the axis of the transmissometer, partial blockage of the instrument occurred and lasted some three hours. It eventually cleared as the result of a general thaw. Some versions of this transmissometer incorporate a blower to keep snow out of the collimator tubes but such a technique can lead to difficulties over the non-uniform disturbance of the atmosphere within the optical path, especially in fog conditions. The Mk 4 transmissometer was not blocked by the snow, although this may have been because the snow was blown into the Mk 4 transmitter which has quite a large heat dissipation. Had it been blown towards the receiver it is likely that the Mk 4 would have been blocked.

5.2.2. *Analysis A—results*

The plot of Mk 4 output against the Erwin Sick output for homogeneous visibility occasions is shown in Figure 11. There is clearly a strong correlation between the outputs of the two instruments but the distribution of the data about its mean at any Mk 4 value can be shown to be non-normal. The existence of individual extreme values which will seriously distort the standard deviations calculated from the data is also evident. There is an apparent offset between the two instruments at a visibility of 100 m and this is preserved in all the results of the SM 414 (see Figures 12 and 13). Such an offset could arise in at least three ways. There could be an offset in the amplifier in the Mk 4 but if this were so it would have shown up in the results taken at the same time with the PVM and from Figure 17 it can be seen that it is not evident. Since the SM 414 is a folded-beam

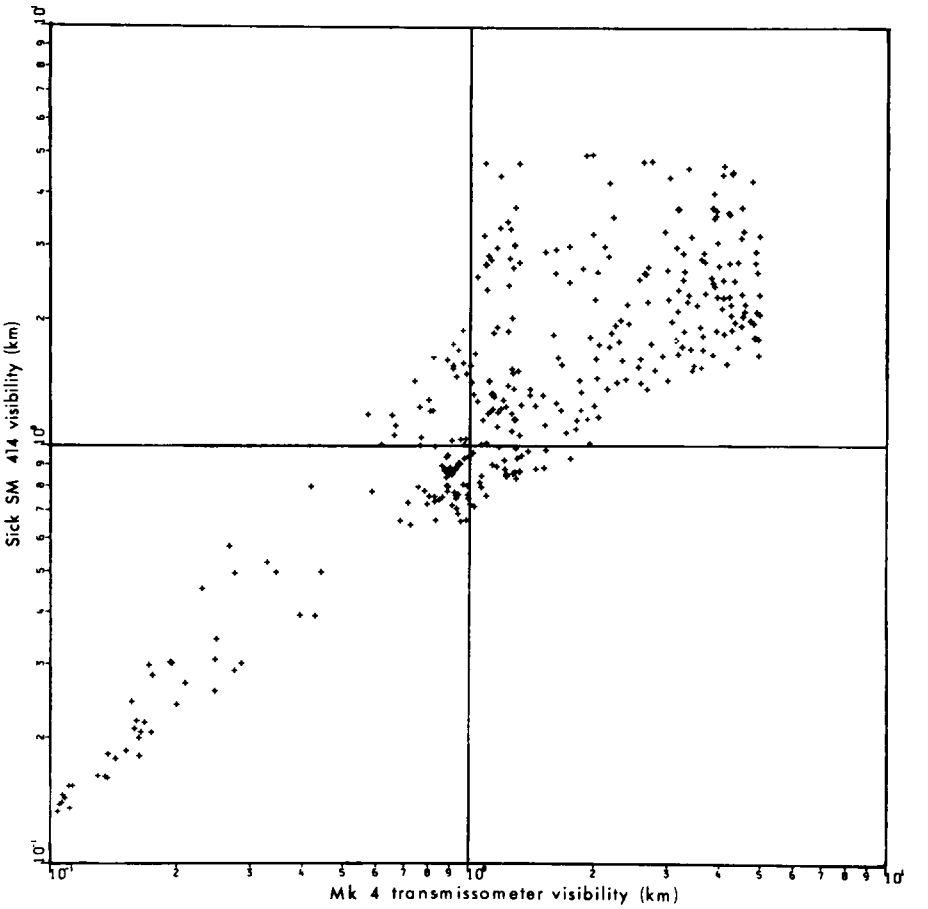

FIGURE 11. Results of the Erwin Sick SM414 analysis A

Visibility in the range 100 m to 5 km; no precipitation during previous 1½ hours
Wind speed more than 3 kn, visibility changes less than 1% per minute.
$V_{TM} = 1.95$ V $V_{TO} = 0.00$ V $d_o = 4 \times 3.75$ m

device, it is possible for back-scattered light to be returned to the detector, thus generating an excess signal. This effect would probably increase significantly as the visibility decreased and would therefore result in a non-linear tail on Figures 11 and 12 at low visibilities. There is no evidence of such a distortion and so the most likely explanation of the intercept on Figure 11 is that there was a standing voltage offset in the electronics of the instrument. This point could not be checked physically because the device had been returned to the manufacturer before the effect was discovered.

The results of the accuracy analysis are shown in Table III in terms of the mean and standard deviation of the differences between the Mk 4 and the SM 414 at the mid-points of the three intervals of visibility chosen. Clearly, for the relatively small number of observations available, the agreement between the Mk 4 and the SM 414 is good. The very large standard deviation at 1000 m is due to the effects of a single point for which the Mk 4 visibility was 1100 m and the SM 414 was 5000 m. If this point is excluded the standard deviation for 51 observations is reduced to 44 per cent.

5.2.3. *Analysis B—results*

The equivalent results to those discussed above are presented in Figure 12 for all the data gathered and in Table III for all the data in the selected bands. For Figure 12 the constants used were the simple first-guess estimates; the geometrical distance between the optical surfaces of the principal lenses was used to calculate the length of the base line. The relationship is clearly non-linear and, as for the restricted data set, the distribution can be shown to be non-normal. The correlation at low visibilities does not seem in general to be significantly worse than in the restricted data set, although the presence of a few points lying well away from the general trend once again gives rise to a rather large standard deviation. The apparent split of the data into two distinct groups at very low visibilities was traced to a set of readings taken on a particular occasion of very wet fog but is retained because such effects cannot be discriminated against operationally. At high visibilities the scatter is considerably worse than at low visibilities; however, this may not be too serious a problem since really accurate determination of visibilities above 3 or 4 km is largely an academic problem and quite large absolute errors can probably be tolerated. From Table III it can be seen that in the mean the agreement between the SM 414 and the Mk 4 for all the data is at least as good or even marginally better than that for the homogenous subset, although, as would be expected, the variability is greater, especially at low visibilities.

5.2.4. *Analysis C—results*

The results obtained in rain are shown in Figure 13 and Table III; they follow the same format as the others. The scatter on Figure 13 appears qualitatively smaller than for either of the other cases and, indeed, the standard deviations in Table III bear this out. The agreement in the mean is not significantly different at low visibilities from that found for the other data but at high visibilities it is significantly worse. On Figure 13 there is a suggestion at high visibilities of a split of the data into two populations but we have not been able to establish any convincing argument as to why this should be so. It is no doubt a major factor, however, in the large discrepancy between the mean values obtained from the SM 414 and the Mk 4.

TABLE III. *Summary of the comparisons between the Mk 4 transmissometer and the observers and all other instruments*

		Nominal visibility of observers or Mk 4							
		150 m		1000 m		3000 m		10 000 m	
Comparison	Analysis	$(d \pm s)$%	n	$(d \pm s)$%	n	$(d \pm s)$%	n	$(d \pm s)$%	n
Mk 4 – Observer		(9± 60)*	58	(2± 20)*	12	(−14± 40)*	54	(−18± 75)*	127
Erwin Sick – Mk 4	A	(33± 20)	26	(23± 70)	52	(−18± 25)	10		
	B	(22± 40)	415	(29± 70)	432	(−13± 35)	56		
	C	(29± 20)	39	(26± 40)	114	(−37± 15)	11		
Marconi – Mk 4	A	(4± 10)	14	(1± 3)	5	(−20± 25)	39		
	B	(1± 40)	182	(8± 40)	78	(−21± 20)	131		
	C	(−10± 13)	14	(−2± 5)	40	(−12± 25)	14		
PVM – Mk 4	A	(5± 20)	30	(−5± 30)	62	(−6± 20)	32		
	B	(55± 190)	247	(13± 60)	346	(−3± 30)	112		
M.R.I. – Mk 4	B	(11± 110)	119	(−57± 30)	75	(−56± 25)	57		

Mean (d) and standard deviation (s) of the difference in the two measurements of visibility expressed as a percentage of the visibility (n is the number of observations).

* Average value of s and $|-s|$ derived from equal ± errors on transmission comparison.

A = well-mixed fogs and hazes, B = all data, C = rain and drizzle.

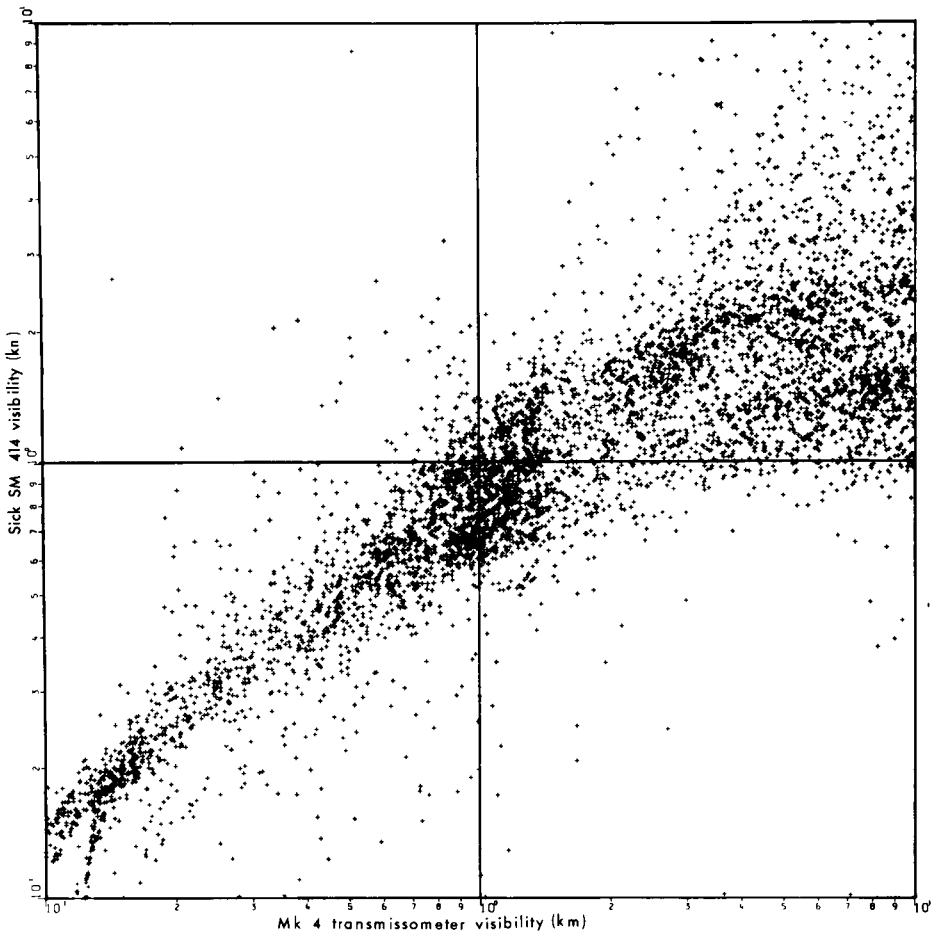

FIGURE 12. Results of the Erwin Sick SM414 analysis B
Visibility in the range 100 m to 10 km
$V_{TM} = 2.00$ V $V_{TO} = 0.00$ V $d_o = 4 \times 4.5$ m

5.2.5. *General discussion*

In the analysis of the complete data set a value of $V_{TM} = 2.00$ V was used. An inspection of V_T when the Mk 4 visibility was 12 km or more gave a mean value of $V_{TM} = 1.95$ V and all the other analyses were done with this value. The parameter d_o is also open to adjustment because the effective optical path length may not be equal to the geometric path length. This can arise when the attenuation which occurs within the baffles of the telescope and projector is different from that in the free atmosphere between the apertures. For the analysis of the complete data set, a path length of 4×4.5 m was used which is the maximum path possible and assumes that the air inside the baffle tubes was the same as the free air. For the other analyses a value of 4×3.75 m was used, which is based upon the assumption that the air inside the baffles is half as opaque as the free air. This reduced the calculated visibility by 20 per cent but from Table III it is clear that on average the SM 414

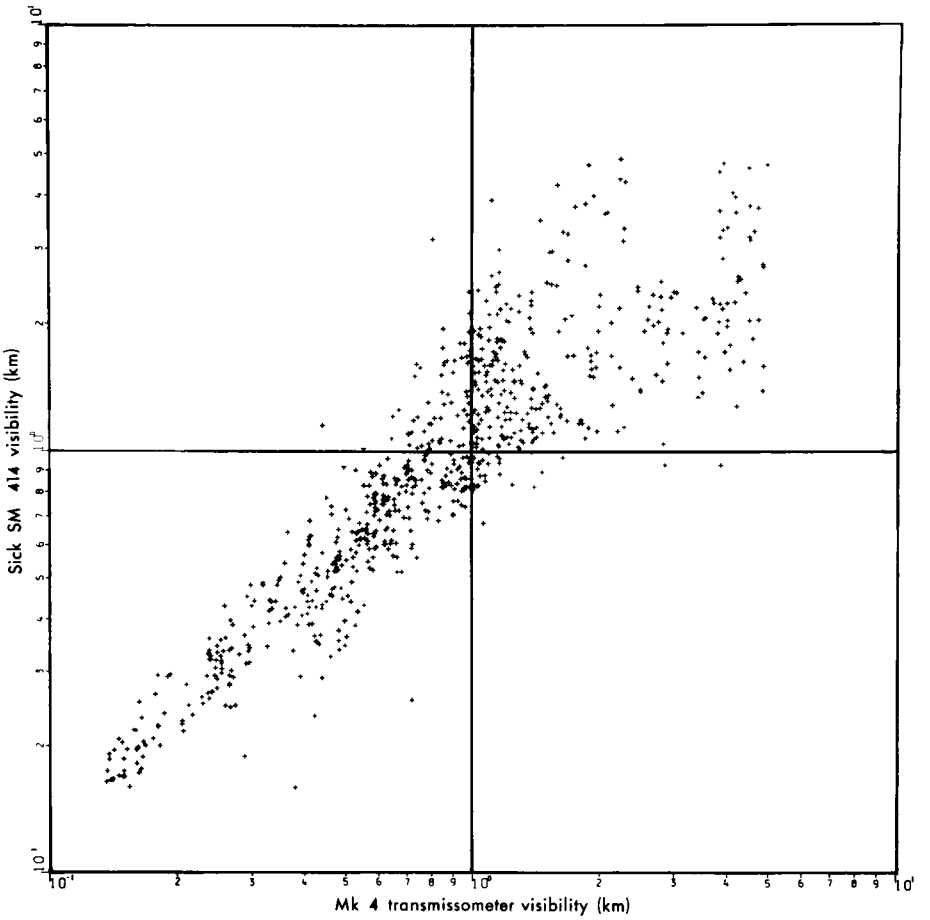

FIGURE 13. Results of the Erwin Sick SM414 analysis C

Visibility in the range 100 m to 5 km; only observations with precipitation during the previous 1½ hours
$V_{TM} = 2.00$ V $V_{TO} = 0.00$ V $d_o = 4 \times 3.75$ m

still yielded values well in excess of the Mk 4 for visibilities in the range 100 m to 1000 m and less than the Mk 4 for higher visibilities.

Although visual inspection of Figures 11 and 12 indicates that the extreme points have been removed by the application of the criteria designed to reject inhomogenous occasions, the improvement in the agreement with the Mk 4 is not very marked. A close inspection of the extreme points on Figure 11 suggested that the instrument was temperature-dependent. The output voltage from the SM 414 was therefore linearly correlated against temperature for occasions when the Mk 4 visibility was in the range 10 – 12 km. The coefficient so derived for transmission values was −0.6 per cent per degree Celsius (124 observations, regression coefficient 0.92). The reference voltage (see section 3.2) was also linearly correlated against air temperature and yielded a coefficient of +0.07 per cent per degree Celsius (1699 observations, regression coefficient 0.41). The

linear combination of these two effects produced an overall correction of −100 metres per degree Celsius at a visibility of 1 km. The very small contribution to this correction that arose from the temperature-dependence of the reference voltage suggests that the effect is optical rather than electronic. Further investigation of this problem was prevented because the instrument had to be returned to the manufacturer before these results were apparent.

5.3. *The Marconi MET 1*

5.3.1. *Instrumental considerations*

After initial difficulties with the installation of the equipment it performed reliably until the autumn of 1978. The compensation features (see section 3.3) appear to have worked well. Over an 18-month period the average change of the reference level, which compensates for lamp ageing and contamination of the transmitter/receiver optics, was −0.34 per cent per month. The contamination of the retro-reflector, which is compensated, was on average −0.1 per cent per month. Had these changes not been automatically compensated for then it can be shown by the use of equations (2) and (3) of section 2 that after one month a visibility of 1 km would have been measured as 700 m. One of the main problems experienced was caused by spiders' webs, which required the instrument to be cleaned a few times during the trial.

In the autumn of 1978 some instability of the output was noticed. The instrument was thoroughly cleaned and an attempt was made to set up the alignment. This proved a very difficult task as there was inadequate provision for adjustment. It was noticed that the beam pattern was not very uniform and the problem was further exacerbated by the degradation that had taken place in the efficiency of the LED. Indeed, in order to get sufficient light at the receiver to comply with the manufacturer's recommended signal level for setting up the instrument, it was necessary to focus the beam so sharply that the instrument became very sensitive to any physical distortion of its frame. The results of the fog occasion study reported in section 6 were obtained with the instrument in this condition. Furthermore, the instrument calibration at this time was such that very good visibility (effectively infinite visibility) was being indicated as 2 km and the proportional error in the output voltage was evident at all lower visibilities.

Before this instrument (which was a prototype) could be used operationally it would be essential for it to embody adequate facilities for the control of the alignment and for the easy exchange of the LED.

The period of moderate snow referred to in section 5.2.1 caused the blockage of the collimator tubes in this transmissometer as well as in the Sick device. The clearance time for this instrument was considerably longer, however, at around 5 hours.

5.3.2. *Analysis A—results*

The results of the comparison for well-mixed fogs and hazes are shown in Figure 14 and Table III. These results were obtained with optimized system constants and a base length of 2 × 2.3 m, which is equivalent to the assumption that the air in the baffle tubes is half as turbid as that outside. The comparison shows a non-linearity although the agreement at visibilities below 1 km is very much better than was the case for the Sick SM 414. Indeed,

given the residual atmospheric variability and the combination of instrument errors, it is doubtful whether the agreement between two such devices could be expected to be much better than this. It is prudent to note, however, that the result at 1000 m is based on only five observations and may contain an element of good fortune. At higher visibilities the agreement weakens but, as before, we may ask whether a larger absolute error can be tolerated in this range.

In all the results from this instrument (Figures 14, 15 and 16) there is a distinct, non-linear tail to the graphs at visibilities below 150 m. At this level of visibility the Mk 4 is reaching the lower limit of its sensitivity since the transmitted light is down to 2 per cent of the maximum intensity. It is then very sensitive to any change in the offset of the amplifier (V_{TO}). The comparison with the M.R.I. Fog Visiometer (see section 5.4) was done at the

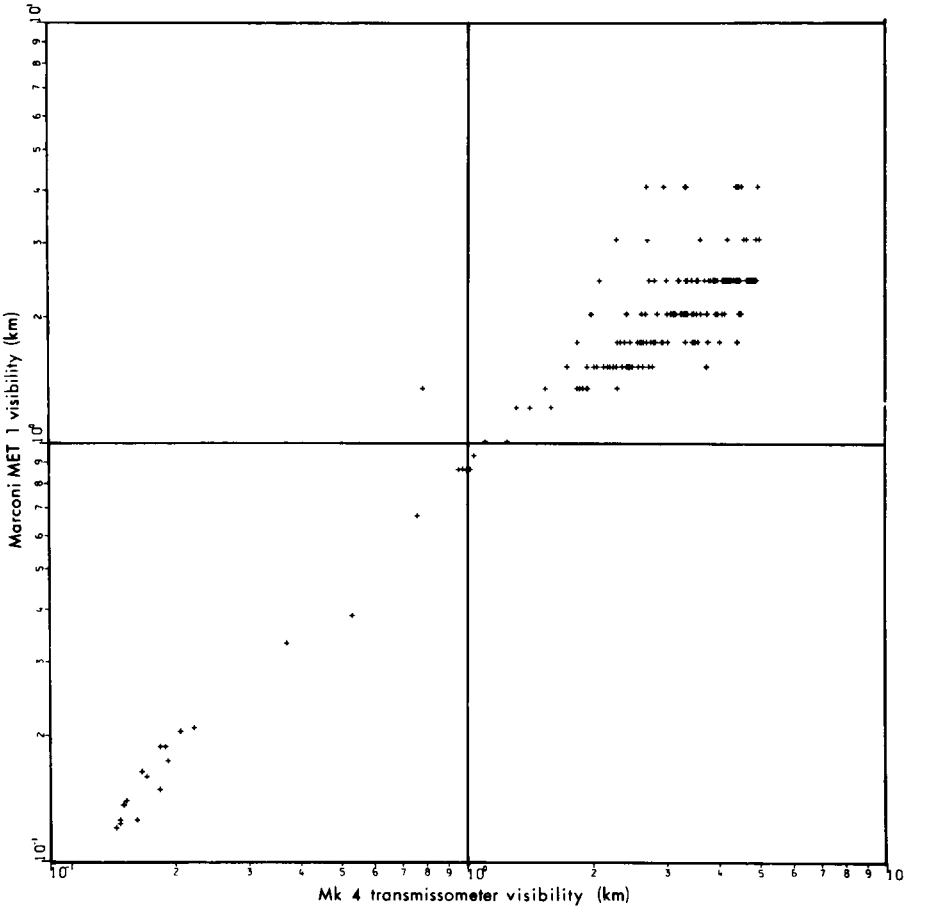

FIGURE 14. Results of the Marconi MET 1 analysis A for the period 7/2/77 – 6/5/77
Visibility in the range 100 m to 5 km; no precipitation during previous 1½ hours
Wind speed more than 3 kn, visibility change less than 1% per minute.
$d_o = 2 \times 2.3$ m

same time as this one and shows a similar trend. It is likely, therefore, that this feature of the results was due to a drift in V_{TO} for the Mk 4 amplifier.

Notwithstanding the rather small number of points assessed in Table III particularly at the 1000 m visibility, there are some grounds for the view that the Marconi MET 1 does compare satisfactorily with the Mk 4 transmissometer.

5.3.3. *Analysis B—results*

The results of the analysis of all the data, carried out with the non-optimized constants ($d_o = 2 \times 2.0$ m which was the maximum free air path) are shown in Figure 15 and Table III. The digital resolution of the output of the MET 1 is clear from Figure 15 on which the data at the 12 km ordinate represents the least significant bit generated by the instrument.

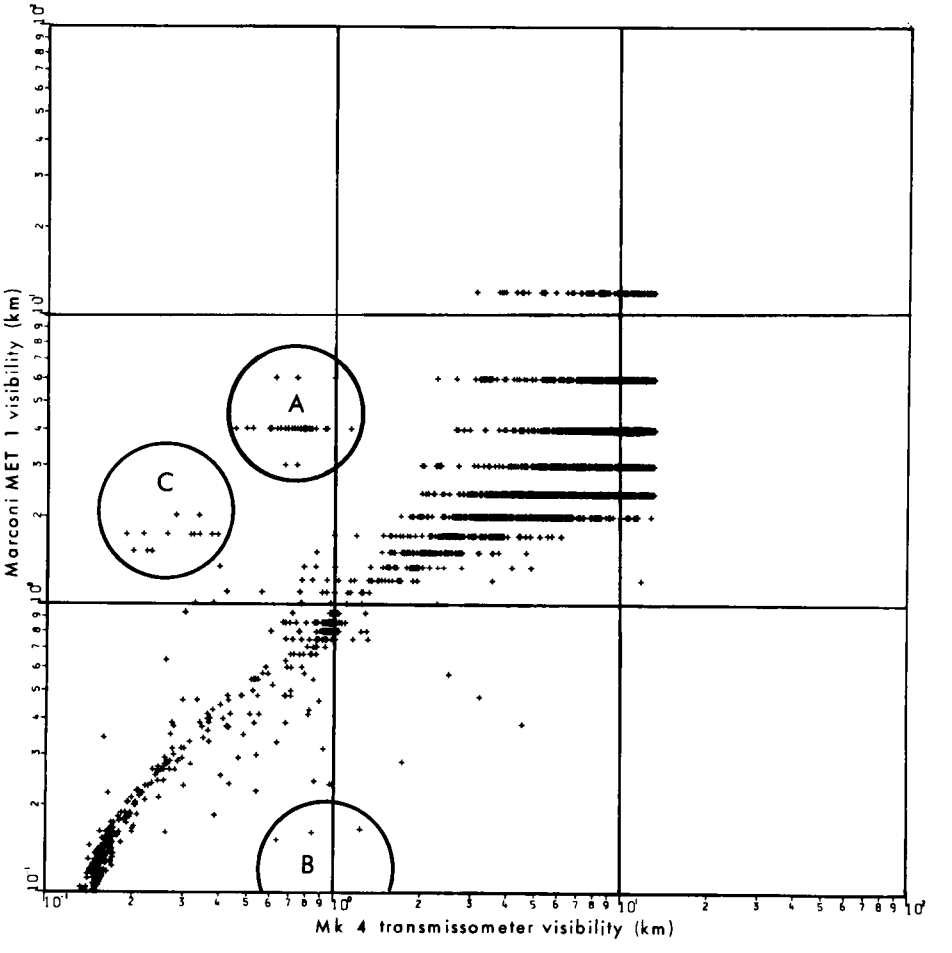

FIGURE 15. Results of the Marconi MET 1 analysis B for the period 7/2/77 – 6/5/77

Visibility range 100 m to 13 km, no other restrictions

$d_o = 2 \times 2.0$ m

A, B and C refer to section 5.3.3.

A value of zero bits can be generated and implies infinite visibility, but such data have been discarded.

It was pointed out in section 4.2 that in computing the means and standard deviations shown in Table III, the data were restricted to values of visibility greater than 100 m and less than 5 km. However, for the MET 1 we excluded from the 100 – 200 m range those points marked C on Figure 15, while in the 900 – 1100 m range we excluded those points at 3 km, 4 km and 5 km in the group marked A. In the 100 – 200 m range, the inclusion of those points marked C would raise the standard deviation from 40 to 93 per cent, but it is probable that these particular results are not representative of the normal performance of the instrument. During the period when these results were taken, the MET 1 and the M.R.I. instruments both recorded visibilities at about the 1.8 km level and, indeed, both responded in the same way at the same time to changes of the order of 200 – 300 m. The Mk 4, however, showed a violent drop in visibility from about 2.3 km to 300 m in this period followed by a rapid recovery, and we believe this to have been due to an artificial obscuration of the beam, probably by an insect or bird, or to some undiagnosed temporary fault of the equipment. The points marked A on Figure 15 also appear to have arisen as the result of some effects in the Mk 4. The visibility recorded by the M.R.I. instrument at the same time agreed well with that given by the MET 1 but the output from the Mk 4 changed in a random fashion in the range 400 m to 1 km. The visibilities recorded by all three instruments on either side of the period were steady in the range 3 – 5 km. At the start of the period the relative humidity was 71 per cent and it increased to 92 per cent by the end of the period, the variation in the Mk 4 output is therefore unlikely to have been caused by fog, and a bonfire is also an unlikely cause since the time period involved was 1600 – 1715 hours on a January evening. The most likely explanation again seems to be that an insect affected the Mk 4 transmission path, perhaps by crawling across the entrance or exit lenses of the receiver or telescope. In any case, the exclusion of these points from the statistical analysis of Table III seems well justified.

The points marked B also seem somewhat anomalous and, although they fall outside the visibility bands analysed, are worthy of comment. They were recorded in a 5-minute period before and after which the MET 1 was indicating 3 km and the Mk 4 transmissometer 4.5 km. During the period the MET 1 measured a visibility of 150 m and a similar dramatic drop in visibility was shown by the M.R.I. The Mk 4 registered three readings of 1.2 km, 800 m and 600 m. The relative humidity was 92 per cent and the time was 0300 to 0305 hours. Once again, therefore, neither fog nor a bonfire can be regarded as likely. A power failure, rapidly restored, might have produced this effect but there is no other evidence to support the idea that one occurred. No satisfactory explanation of these points has been found.

5.3.4. *Analysis C—results*

The results of the comparison between the Marconi and the Mk 4 on rain occasions are shown in Figure 16 and Table III. The features of Figure 16 are similar to those of Figures 14 and 15 and the discussion given for those figures applies equally to this one. From Table III it is clear that the MET 1 behaves at least as well in rain as it does in well-mixed fogs and hazes and that none of the general increase in variability from the specially homogeneous occasions to all occasions can be attributed to the performance in rain.

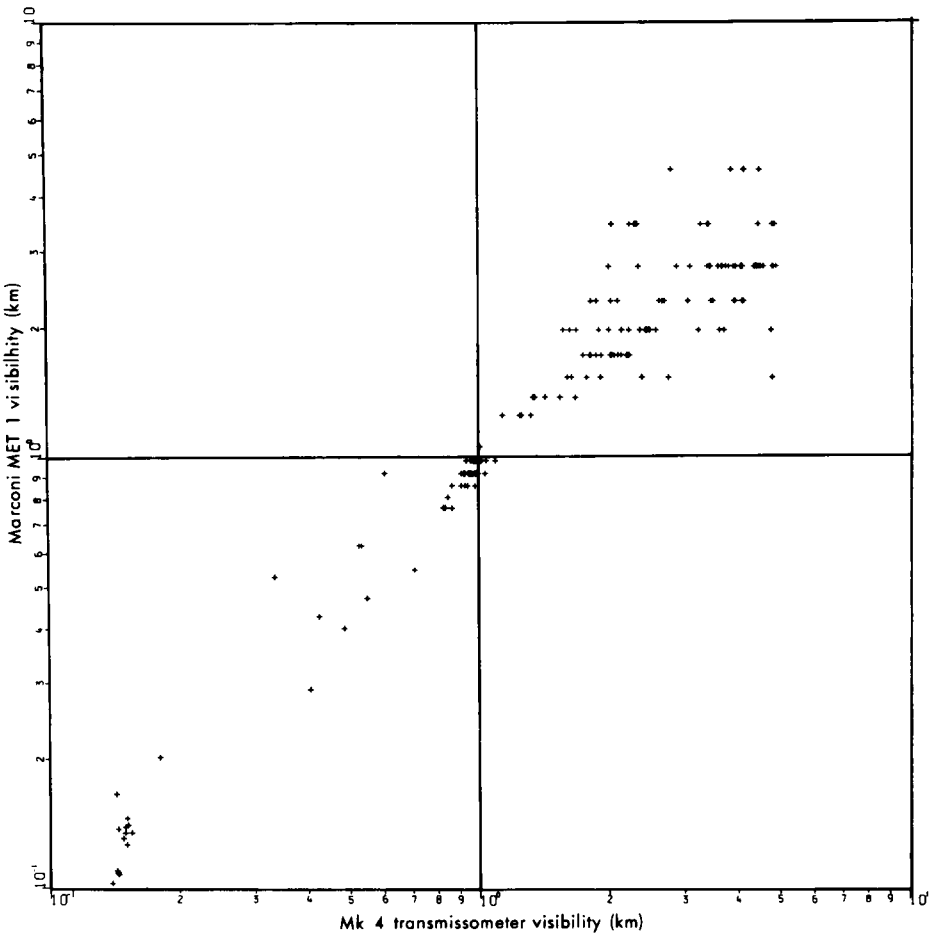

FIGURE 16. Results of the Marconi MET 1 analysis C for the period 7/2/77 – 6/5/77
Visibility range 100 m to 5 km; observations in precipitation only
$d_o = 2 \times 2.3$ m

5.3.5. *General discussion*

The Marconi MET 1 used in this study was a prototype instrument which had many design and operational shortcomings. Nevertheless, it compared very well with the Mk 4 transmissometer and showed that a single pole transmissometer employing a folded path can give results comparable to those of a 200 m base-line transmissometer. The uncertainty about the actual optical path to be used in the calculation of visibility which was discussed in section 5.2.5 for the Sick SM 414 applies also to the MET 1. Provided that the instrumental problems discussed in section 5.3.1 are tackled in any production instrument and provided the difficulties with spiders and insects can be either overcome or tolerated, then this device would be an acceptable alternative to the Mk 4.

5.4. *The Plessey Point Visibility Meter*

5.4.1. *Instrumental considerations*

The Meteorological Office already has considerable experience with PVMs. Douglas *et al.* (1978) and Thorn (1973) describe work using either the 1.5 km version or the 5 km version. This part of the report continues the work reported in Douglas *et al.* PVMs have worked reliably on land but are subject to spurious output due to optical degradation by spiders' webs and insects. Tests performed using some cream (supplied by Plessey) to repel insects indicated that the cream became ineffective after at most a few weeks.

There have been two PVMs deployed on the instrumented buoy DB1. In both cases the LED failed after a short time. On this buoy the PVM was switched on for a short period each time a reading was taken, and it was suggested that this might have caused the failure of the LED. To test this, a PVM, located as shown in Figure 4, was switched on for a period of 7 minutes at half-hourly intervals. The operation was carried out regularly for 10^4 cycles without any detrimental effect to the instrument which suggests that, in itself, switching the power to the LED does not cause it to fail.

It has been suggested that in a marine environment with salt steadily encrusting on the lenses the control circuitry for the LED caused it to be overdriven, with the result that it failed. Plessey's own power supply would have been incapable of blowing the LED, but the one used on DB1 was not a Plessey unit and may have been able to supply too much current. It would seem desirable that for any PVM there should be an independent safeguard to prevent the LED being overdriven and an output which permits a check that the LED is still within its control region. For low-power usages, it would be desirable to power the lens heaters separately from the other circuitry so that, as a power conservation measure, the lenses could be cleaned before the sensor circuitry is switched on.

5.4.2. *Analysis A—results*

The results of the comparison between the PVM and the Mk 4 in homogeneous conditions are shown in Figure 17 and Table III. The constants K and V_{SO} used for this analysis were optimized by linear regression in the range 100 m to 1000 m and were $K = 0.095$, $V_{SO} = 0.048$ volts. The value of V_{SO} obtained was checked against a value obtained by direct measurement in very good visibility conditions and the two were found to agree well. Clearly, the PVM is highly linear with respect to the Mk 4. The close average agreement between the instruments is to be expected since the PVM is calibrated against the Mk 4. The variability of the results (Table III) is not strongly dependent upon visibility and is comparable with those of the other transmissometers when they are matched against the Mk 4 and we conclude that the intrinsic capability of the PVM to measure visibility is certainly as high as that of the transmissometers.

5.4.3. *Analysis B—results*

An idea of the correspondence between the measurements of the PVM and those of the Mk 4 in full operational conditions is given in the all-data plot of Figure 18 and in Table III. There is no sign of any deterioration in the linearity of the PVM but the variability of the results is substantially increased. For these results, the values of K and V_{SO} found previously (Douglas *et al.* 1978) were used ($K = 0.089$ km V^{-1} and $V_{SO} = 0.018$ V). It is

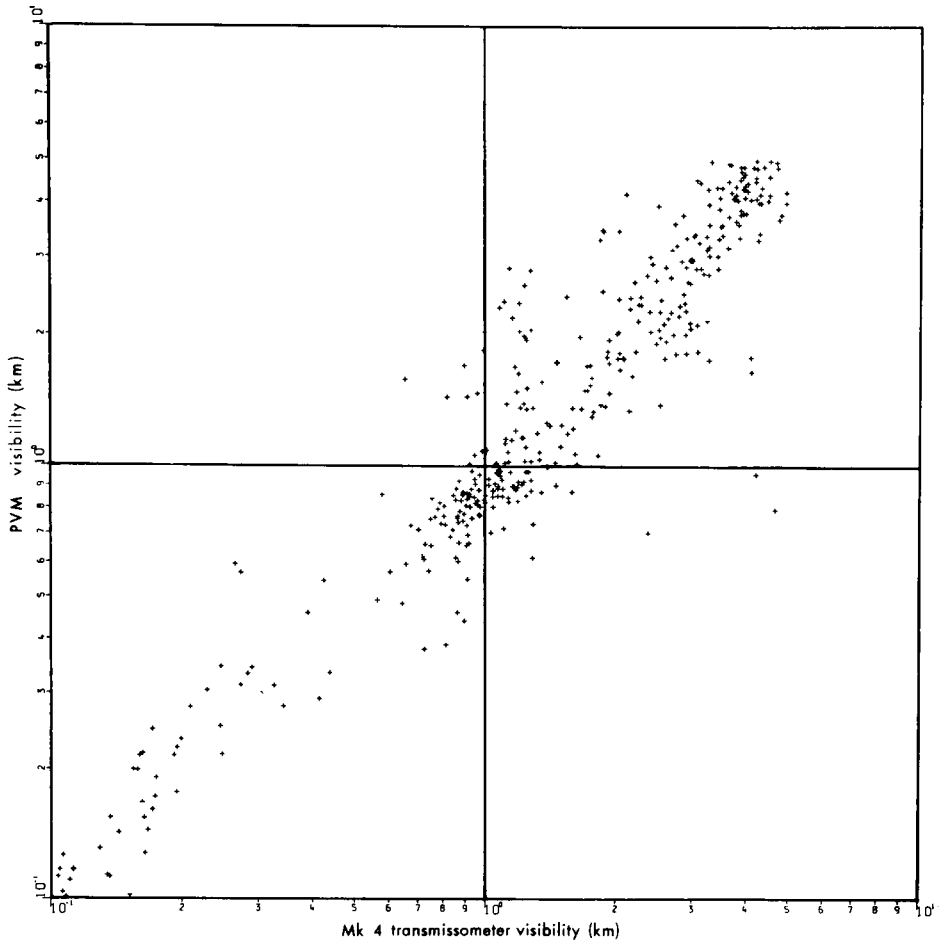

FIGURE 17. Results of the Plessey Point Visibility Meter analysis A

Visibility range 100 m to 5 km; no precipitation during previous 1½ hours
Wind speed more than 3 kn; visibility changes less than 1% per minute; temperature above 0 °C.
$K = 0.095$ km V $\quad V_{SO} = 0.048$ V

noticeable that the largest increase in variability occurred at low visibility values. The PVM is expected to be at its best in fog whereas the Mk 4 is reaching the lower limit of its usefulness around 100 m. We might reasonably conclude then that, at least in the region 100 m to (say) 800 m, the very large increase in variability is mainly due to the fact that the small sample volume of the PVM leads to correct but unrepresentative measurements relative to those provided by the Mk 4, or to the inaccuracies that arise when the PVM is sampling rain or drizzle. The usefulness of the PVM in this operational role therefore seems very limited unless some correction can be devised to eliminate precipitation errors and some sort of spatial or temporal averaging can be applied to improve the representativity. The question of the possible averaging of the output has been separately considered and is discussed in section 6 of this report; the precipitation problem is discussed in section 5.4.4 below.

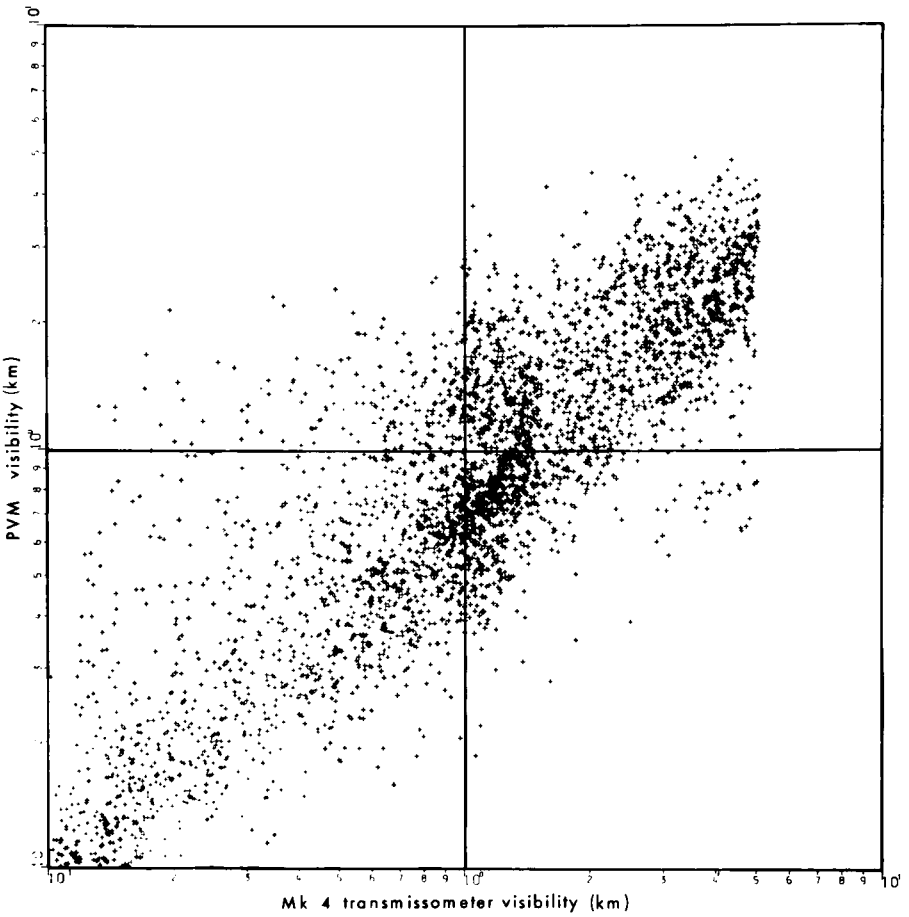

FIGURE 18. Results of the Plessey Point Visibility Meter analysis B
Visibility range 100 m to 5 km; all data
$K = 0.089$ km V $V_{SO} = 0.018$ V

5.4.4. *Analysis C—results*

The PVM is designed as a fog measurement device and is not expected to perform correctly in precipitation of any sort. A rain funnel was constructed to prevent the instrument from generating an output from water splashed off the instrument case during precipitation. This funnel is shown in Figure 3. The tube allows rain to pass freely through the sampling volume of the instrument but prevents rain-water from running down from the top surface of the instrument into the sample volume and rain from splashing from the side walls of the case into the field of view of the detector. The performance of the PVM with and without the rain funnel is discussed.

The errors which arise when the PVM is used in conditions other than fog or haze originate mainly with the significant differences in scattering functions between the different types of particle and with the sampling efficiency of the instrument for large

precipitation particles. In this work no attempt has been made to distinguish between these two effects. The calibration curve for the PVM under differing conditions is shown in Figure 19 which has been compiled from the results obtained in the present work and from other previous work. Data for conditions when the temperature was less than 0 °C could not be used to provide K and V_{SO} by linear regression because with no independent check of V_{SO} available there was no means of ensuring that the values so obtained were reasonable. Therefore a value of 0.050 volts was assumed for V_{SO} (which is typical of all PVMs we have used) and this, together with the centre of gravity of the data points was used to define K. If the calibration curve for fog is used in all conditions then, on average, visibilities in rain conditions will be indicated about 30 per cent too low while for snow they will be about 40 per cent too high. In snow, with wind speeds greater than 5 kn, the instrument overreads by a larger value. However, the fact that data taken for temperatures above and below freezing give similar calibration curves suggests that changes of particle size distribution in fogs and freezing fogs are not significant.

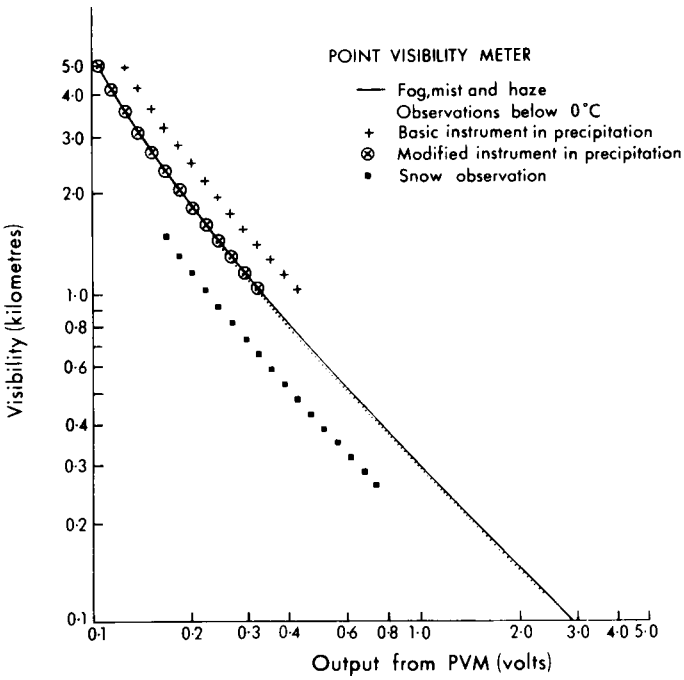

FIGURE 19. The calibration characteristics of the Plessey Point Visibility Meter under various conditions

Data taken in rain with the PVM modified by the rain funnel are also shown on Figure 19. The calibration of this modified design in rain conditions was very similar to that for the unmodified PVM in fog conditions but, given the complexity of the sampling method and of the light scattering properties of raindrops, this agreement can only be regarded as fortuitous. Further work would be necessary to substantiate the full performance of the PVM with the rain funnel but fundamentally it is difficult to see how any such device can overcome the problem of the difference in the scattering physics between fog/haze and rain or other precipitation. From the size of the tube used in the funnel it would not be

expected to sample snow efficiently. The period of moderate snow discussed in connection with the two short-base-length transmissometers did not cause any blockage in the PVM but the visibilities recorded during the snow were much higher than those recorded simultaneously by the Mk 4.

5.4.5. *Sampling problems in the PVM*

There are numerous examples in the data gathered during these experiments of significant differences between the visibility yielded by a PVM and that given by the Mk 4 transmissometer in conditions of light winds. Typical cases are shown in Figures 20 and 21. Figure 20 shows that during a period of very light winds from 1930 to 2100 on 13 December 1976 the PVM consistently overread with respect to the Mk 4. Once the wind increased beyond about 0.75 m s^{-1} (1.5 kn) the agreement between the two instruments improved though not in a sustained or systematic manner. In other results we saw a definite inverse correlation between PVM visibility and wind speed (see Figures 30, 31). In Figure 21 there is an example of a further effect apparently dominating this wind feature. Following an extended period of very light winds in which the PVM output was very variable and did not agree well with the Mk 4, the two measurements converge as the wind

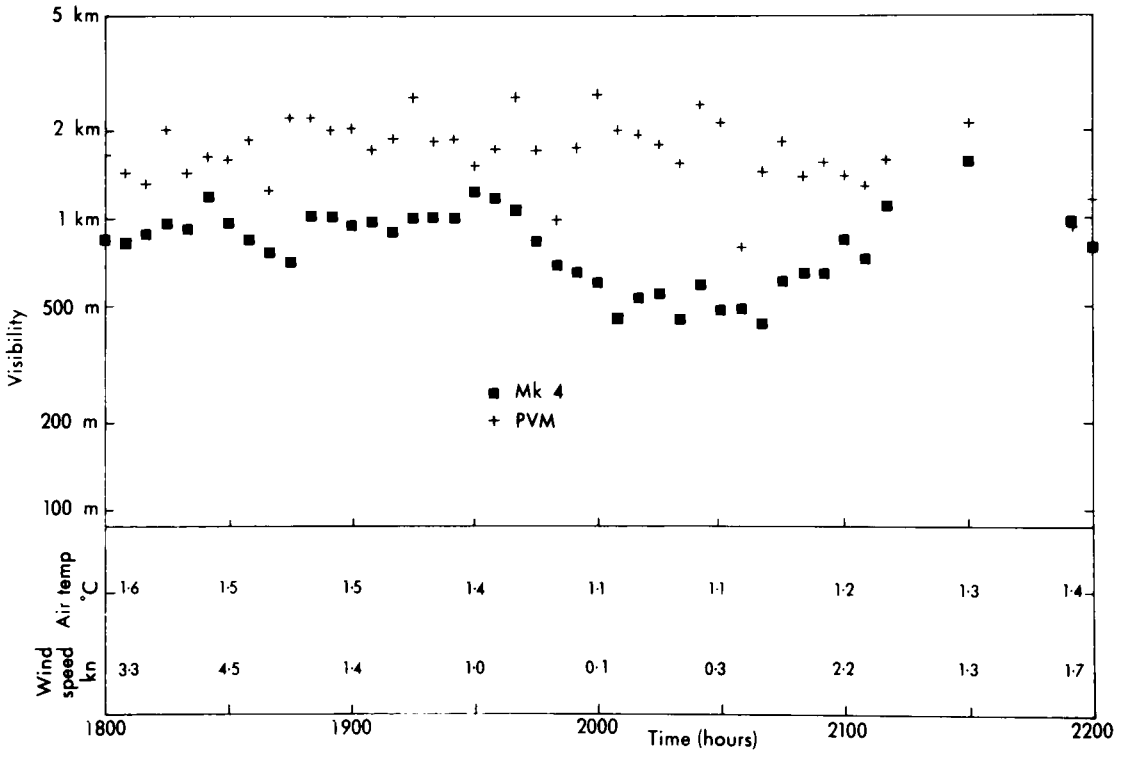

FIGURE 20. Data recorded on 13/12/76 showing the Plessey Point Visibility Meter results obtained in slack wind conditions

picks up. At around 2345, the wind increased sufficiently for the PVM output to become less variable and to follow the changes of visibility very well. However, the two outputs now showed a systematic difference with the PVM indicating a significantly lower visibility than the Mk 4. This state of affairs persisted until 0330 when the two outputs had converged, only to diverge again as the wind slackened, with the PVM then more variable and overreading with respect to the Mk 4. The onset of this period was marked by a very sharp change of air temperature caused by the passage of a warm front at about 2345 GMT. It is clear from these results that in low wind-speed conditions the PVM does not apparently sample the atmosphere successfully and that moreover there may be a significant modification of the fog that it does sample as a result of temperature differences between the instrument and the air surrounding it.

To study these effects, the modification of the fog by the PVM has been described by a simple model and the constants of the model have been measured approximately in a series of experiments. From these results we are able to show that the discrepancies discussed above can reasonably be explained in terms of the interaction between the PVM and the atmosphere.

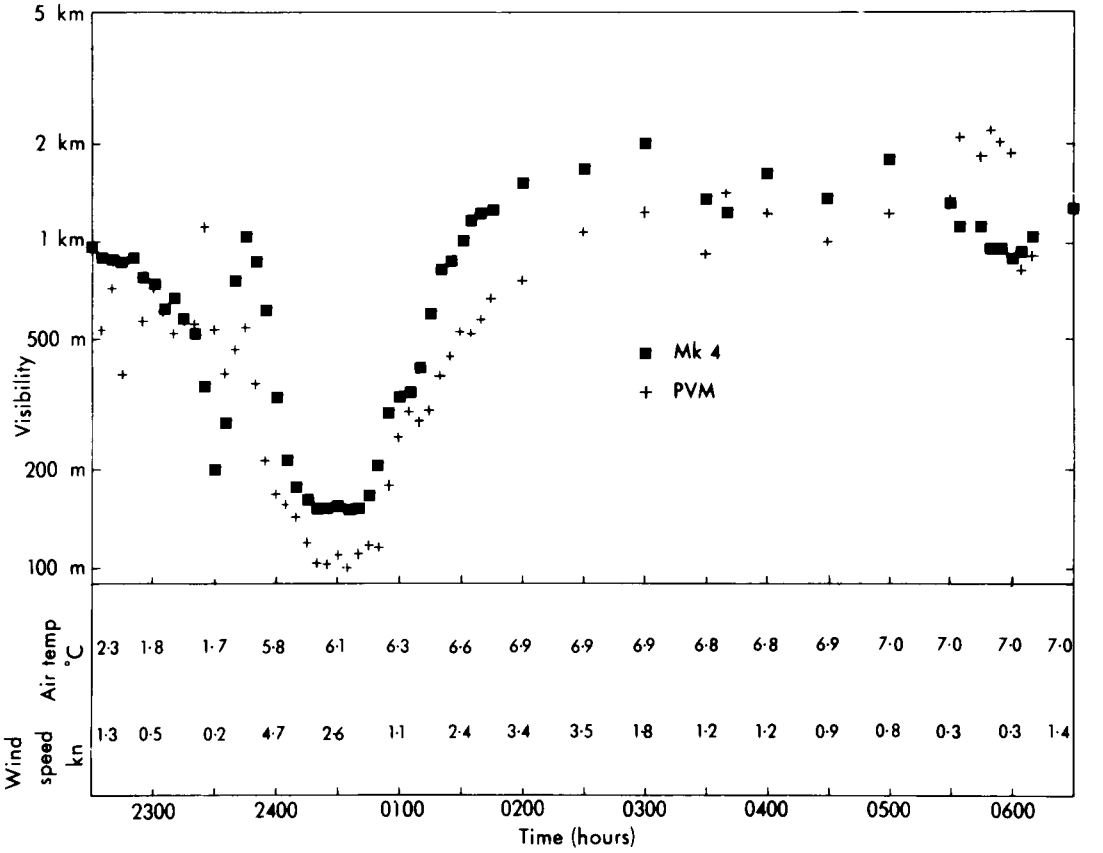

FIGURE 21. Data recorded on 18/11/76 showing the Plessey Point Visibility Meter results obtained during air temperature changes

The most likely mechanisms by which the PVM might modify the fog which it samples are:

(a) evaporation or condensation due to heat exchange between the PVM and the air
(b) impact of fog droplets on to the PVM body by the airstream
(c) diffusion of fog droplets to the walls of the instrument
(d) changes in turbulence which may affect the coalescence mechanisms.

We believe that although the second of these effects may become important if the PVM is exposed in cloud in strong airflows, all but the first one are normally insignificant. The model therefore approximately describes the heat exchange processes between the PVM and the air and yields the changes in liquid water content of the fog which arise from them within the PVM sample volume.

The significant heat-loss mechanisms for the instrument will be radiation and convection and the heat output from it by these two processes under different conditions of airflow were calculated. To calculate the convective heat loss it was necessary to obtain values for the thermal time-constants of the PVM. These figures for three airflow speeds were measured experimentally on the assumption that Newton's law of cooling was valid. Both cooling and heating time-constants were obtained and they were found to be approximately equal.

From these data and a knowledge of the mass of the device, 6 kg, and its specific heat (assumed = 630 J $kg^{-1}K^{-1}$) the power dissipated by convection for a 1 °C excess temperature was computed. The radiative losses for a similar excess temperature were calculated from Stefan's law on the assumptions that the emissivity of the blackened surfaces of the PVM was unity and that the white radiation shield emitted no radiation. For these calculations, the surroundings of the PVM were assumed to be at 0 °C. The results of these experiments and computations are given in Table IV. Also shown in the table as a comparison is the electrical power input to the PVM and it is clear that all these power levels are comparable although the convective losses begin to dominate the radiative losses as the external flow increases.

TABLE IV. *Summary of the power dissipated as heat from a PVM at* 1 °C *above ambient temperature*

Airflow speed	PVM thermal time-constant (1/e)	Radiative power output from PVM at 1 °C excess temp. Air temp. = 0 °C	Non-radiative power output from PVM at 1 °C excess temp.	Electrical power input
m s^{-1}	*seconds*	*watts*	*watts*	*watts*
0	3600	0.5	0.5	3
0.5	1800	0.5	1.5	3
1.5	1200	0.5	2.5	3

Let V be a volume of fog sampled by the PVM and let v m s^{-1} be the external air speed. Winstanley and Adams (1975) have shown that for $v \geq 0.25$ m s^{-1} the flow through the PVM aperture is at least $v/2$. We conducted some experiments using a Porton

anemometer and a hot-wire anemometer in the PVM aperture and confirmed the Winstanley result. So if A is the aperture area, then the rate of sampling a volume is

$$\frac{dV}{dt} \approx \frac{Av}{2} \qquad \ldots(10)$$

Let P_C be the power lost by convection and P_R the power lost by radiation. If the heat input to the fog sample is dh/dV per unit volume then we may write

$$\frac{dh}{dV} = \frac{KP_C + K'P_R}{\frac{dV}{dt}} \qquad \ldots(11)$$

where K and K' are efficiency factors which describe the fraction of the power lost by convection and radiation which goes to modify the fog.

It is not difficult to show that the direct radiative interaction between the PVM and the fog sampled by the PVM is negligible, i.e. K' is very small. However, it is well known that because of latent-heat effects, the air temperature in a fog is generally rather higher than the temperature of the underlying ground and so there will be a radiative heat exchange between the PVM and the ground which could be sufficient to affect the heat available for convective exchange to the air. Fortunately, in the case we have for study, a 5 °C step change in air temperature occurred which clearly left the radiative exchange between the PVM and the ground as a second order effect, so that the complication can be ignored in this instance.

The remaining problem is the value of K and to obtain this an experiment was conducted in which water-vapour exchange was used as an analogue for heat exchange. We assumed that the water vapour evaporated from a wet PVM is transferred by the airflow around it in a manner identical to the heat that passes into the boundary layer of the instrument by conduction. Thus if dm/dV is the increase in the water vapour density in the sampling aperture due to water evaporating from the PVM case and dM/dt is the total rate at which water is evaporated then

$$\frac{dm}{dV} = K \frac{dM}{dt} \Big/ \frac{dV}{dt} \qquad \ldots(12)$$

The surfaces of the PVM were wetted and the increase in relative humidity in the sampling volume was determined with a Vaisala Humicap device for three different wet PVM surfaces and two wind speeds; dm/dV was calculated from these measurements and those of the ambient temperature. dM/dt was measured by applying a known mass of water to the PVM and timing the period taken for it to dry out.

Wetting the upper radiation shield of the PVM produced only very small changes in the relative humidity inside the sample volume; however, when the underside and the curved sides bounding the sample volume were wet, changes in relative humidity in the sample aperture of about 3 and 8 per cent respectively were detected. That the underside of the PVM exerted more influence than the top was consistent with the result of a subsidiary experiment on the airflow paths around the instrument which showed, contrary to other available evidence (Thorn 1973), that the main flow through the aperture was upwards from below the device. A combined value of relative humidity change for the three surfaces was obtained on the assumption that the evaporation (and therefore also heat

loss) was proportional to the surface areas. The values for K then deduced indicates only about 1 per cent of the convected heat actually affects the sampled air. We shall assume that in the speed range 0.25 m s^{-1} to 1.5 m s^{-1} that K is invariant with wind speed and is equal to 0.012.

We now apply this model to the case of the warm frontal passage around 0001 GMT on 19 November 1976 (see Figure 21). It was pointed out above that, for this case, radiative effects can be considered as of second order and we assume, although we have no quantitative knowledge of the electrical dissipation within the instrument, that equilibrium existed between the various sources and sinks of heat before the arrival of the front and that this equilibrium was not significantly disturbed after the frontal passage. Since reasonable visibility was recorded before the front we are justified in believing that none of the post-frontal effects can be attributed to the electrical power dissipation. The external wind speed, v, was 1.5 m s^{-1} at 0020 GMT and temperature difference was 5 °C so that, using the appropriate time-constant from Table IV, the temperature difference after 20 minutes was $5 \times 0.36 = 1.8$ °C. Also from Table IV, the convective power gain to the instrument was therefore $2.5 \times 1.8 = 4.5$ watt. Thus from equation (11), neglecting the radiation term, we have for $A = 7 \times 10^{-4}$ m^2:

$$\frac{dh}{dV} = -4.5 \times \frac{1.2 \times 2 \times 10^{-2}}{1.5 \times 7 \times 10^{-4}} \quad J\ m^{-3}$$

$$\approx -100\ J\ m^{-3}$$

Now the latent heat of vaporization of water at 0 °C is 2.5×10^6 J kg^{-1}, therefore -100 J m^{-3} will result in the condensation of $\frac{100}{2.5} \times 10^{-6}$ kg m^{-3} of water, or 4×10^{-5}kg m^{-3}.

The visibility recorded by the Mk 4 transmissometer at 0020 GMT was 150 m and the PVM was recording a value of 100 m. Roach *et al.* (1976) have reported some simultaneous values of visibility and liquid water content for radiation fogs. There is no simple relationship between these variables as it depends upon the size distribution of the fog droplets but the values given indicate a liquid water content of between 2×10^{-4} kg m^{-3} and 1×10^{-4} kg m^{-3} for a visibility around 60 m and about 5×10^{-5} kg m^{-3} at a visibility of about 150 m. Thus the model predicts that the PVM affected the fog it was sampling both in the correct sense and to about the right extent to account for the difference between the measurements of visibility made by it and the Mk 4 transmissometer.

We may postulate another situation in which the soil temperature is equal to the air temperature and remains constant. From Table IV it can be seen that the electrical power input of 3 W must be balanced by a 3 W loss of heat. This can be achieved when the PVM reaches a temperature 1 °C above ambient in a 1.5 m s^{-1} (3 kn) wind. The model then predicts a decrease in the liquid water content of the fog sample by about 1.5×10^{-5} kg m^{-3}; at higher wind speeds the reduction would be less. This suggests that fogs of only moderate liquid water content (approx. 2×10^{-5} kg m^{-3}) would be completely dispersed by the heat output but this is an over-simplification because a finite time is required to evaporate the droplets and at these air speeds the residence time of the air within the sample volume of the instrument is only about 100 ms. At lower wind

speeds, however, dh/dV is greater and the time available for the modification of the fog is longer. It is under these conditions that the visibility measured by the PVM is higher than that recorded by instruments sampling the unmodified fog. To a first approximation then we have an explanation for the inverse correlation between the PVM output and the wind speed in conditions of constant or only slowly varying temperature.

5.4.6. *General discussion*

The Plessey PVM is a small, robust and convenient unit, properly engineered and easily maintained. Within its limitations it has worked very well. Its output is linear with respect to the Mk 4 transmissometer and given reasonably homogeneous conditions and sufficient airflow it provides as good an indicator of visibility as does any of the transmissometers. Paradoxically, for an instrument designed to measure fog, its operational performance is best at high visibilities because under these conditions there is usually reasonable homogeneity. Indeed, the PVM was the best of the instruments tested for measuring visibilities in excess of 2 km.

Although it was originally designed as a fog measuring device, our results show that it has some serious shortcomings in this respect. There are two problems, one instrumental, the other atmospheric. The instrumental difficulty is that the PVM can significantly modify the fog as it measures it so that incorrect absolute values of visibility result. Visibility trends, however, are not so seriously affected provided that the ventilation rate is sufficient (wind speed in excess of 1.5 m s^{-1}). For lower ventilation rates there is a marked effect both on absolute values and trends and a spurious inverse correlation between wind speed and visibility is apparent in the results. The atmospheric difficulty lies in the fact that radiation fog is highly inhomogeneous and the PVM samples at a point so that simple spot values of visibility show very large variability. Used operationally in this way the certainty that can be attached to the results is very low. Some work is reported in section 6 in which attempts have been made to overcome this problem by rapid sampling and data filtering.

5.5. *The M.R.I. Fog Visiometer 1580*

5.5.1. *Instrumental considerations*

This instrument was loaned to the Meteorological Office for a short time only and a detailed examination of its performance was not possible. Several difficulties were experienced with the device, including trouble with spiders' webs, an awkward cleaning procedure with a one-month schedule, a 30 min warm-up period after initial switch-on and instability in the system constant, K.

5.5.2. *Analysis of results*

Because of the instability in the system constant, K, it was not sensible to carry out all the analyses used for the other devices. All the data obtained has therefore been analysed as a single set with a small sub-set of data obtained in rain.

The all-data plot is shown in Figure 22 and the simple statistics of the whole set in Table III. From Figure 22 it is clear that the data fall into at least two populations, both of which

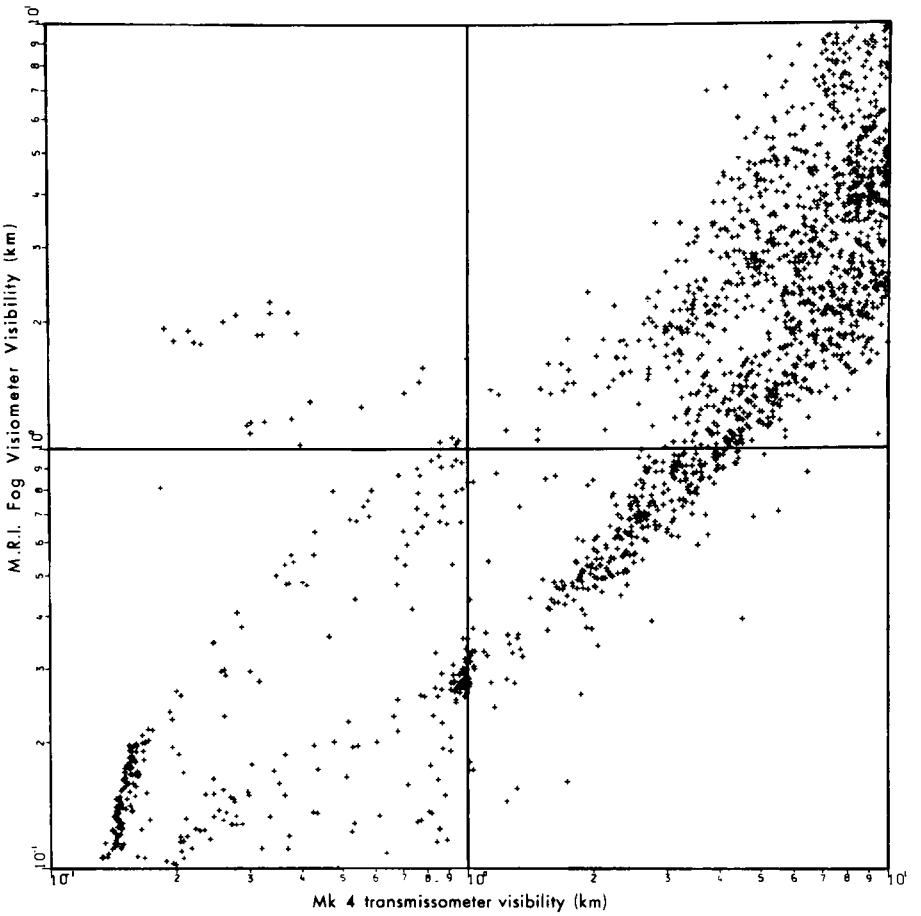

FIGURE 22. Results of M.R.I. Fog Visiometer analysis B for the period 10/2/77 – 6/5/77
Visibility range 100 m to 10 km; no other restrictions

show a marked non-linearity. The first attempt to explain this was aimed at checking for an effect correlated with wind direction because the manufacturer's literature suggests that shielding of the scattering volume can occur. Figure 23 shows a sub-set of the data for which the wind direction was most favourable for instrument exposure but two populations are still evident in the results. The data were then analysed in different time groups and from Figure 24 it can be seen that there were three distinct periods in the observations, each with a different value for the constant K. No satisfactory explanation was found for this although contamination, particularly spiders' webs, could have been the source of the problem. The closest agreement with the Mk 4 is shown in the last of the three periods and the M.R.I. was cleaned and set up at the start of this period.

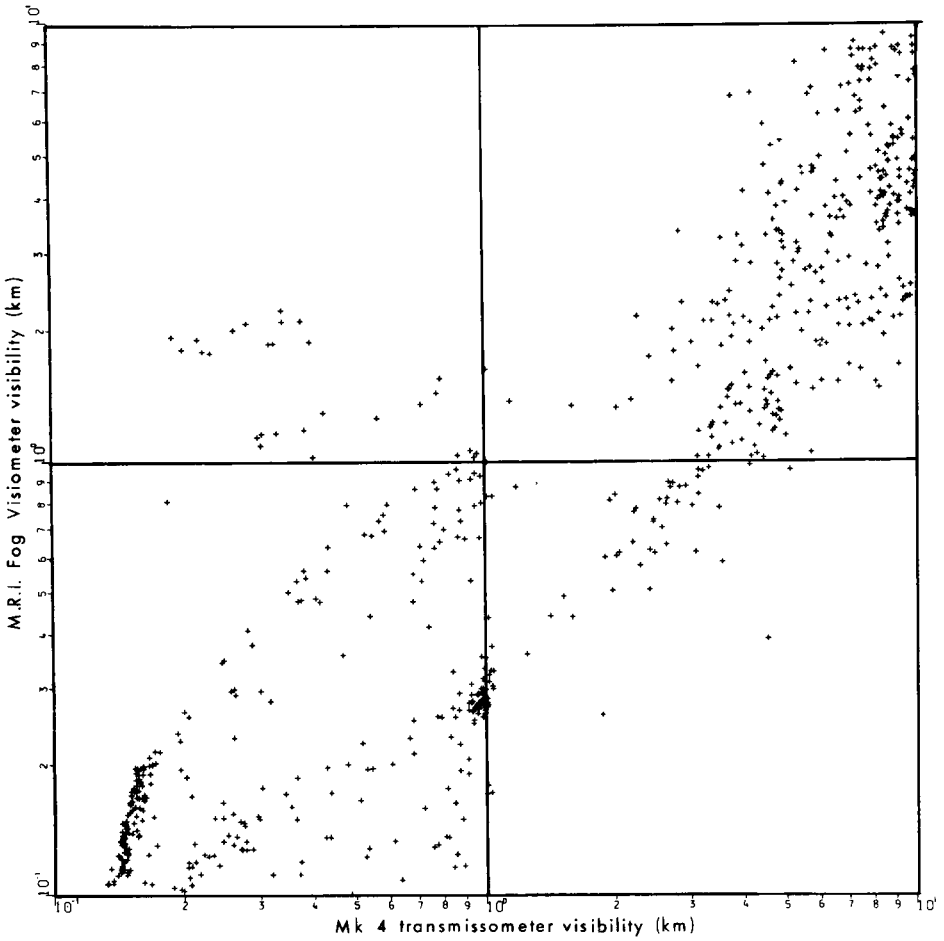

FIGURE 23. Results of M.R.I. Fog Visiometer analysis for most favourable exposure, for the period 10/2/77 – 6/5/77

Visibility range 100 m to 10 km; wind in quadrant south to west only.

Occasions on which data were taken during rain are separately indicated on Figure 24 and it is interesting to note that these data show no marked dissimilarity to the non-rain set. This implies that the exposure of the instrument and the assumptions made in the treatment of the data (see section 2) were adequate even when the scattering from haze and rain particles is compared.

The comparison statistics given in Table III are very poor and, from the information gathered in the limited test period, cannot be improved. Clearly, on this evidence, the instrument cannot be recommended as an operational device although considerably more evaluation is needed before its performance can be adequately described.

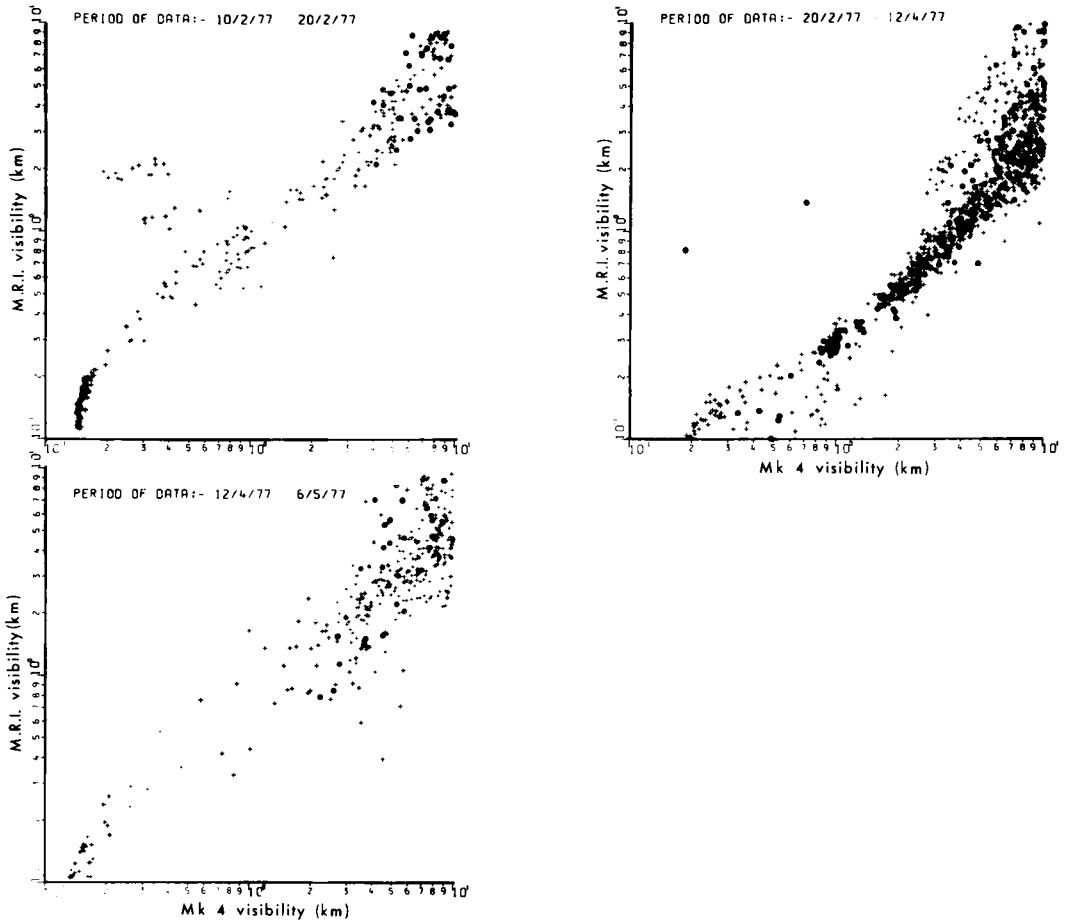

FIGURE 24. Results of M.R.I. Fog Visiometer analysis B in three time periods
Visibility range 100 m to 10 km; no other restrictions.
+ data not in precipitation ● data in precipitation

6. SPATIAL AND TEMPORAL VARIABILITY IN VISIBILITY

6.1 *Introduction*

The problem of the representativeness of the PVM measurements has already been raised in section 5.4.6 and the doubts expressed there decided us to investigate the idea that if the output from a PVM could be sampled rapidly, then the application of a suitable filter to this data stream would result in temporal averaging which might correspond approximately to the spatial averaging performed by a 200 m base length transmissometer and in this way improve the usefulness of the PVM data to the synoptic meteorologist.

6.2. *An experiment*

To test this hypothesis, an experiment was set up in which the output from a 200 m base length transmissometer was compared to that of two PVMs and a Marconi MET 1 arranged along the transmissometer base-line. The physical layout is shown in Figure 4 in which the two PVMs are labelled A and B. The MET 1 was sited at point A along with the PVM and at the same site we mounted a Porton anemometer and wind vane and an electrical resistance thermometer which was housed in an ODAS screen. Only a PVM was at point B.

The instruments had to be mounted at different heights, a point which must be borne in mind when assessing the data. The optical axis of the transmissometer was at the standard height of 3 m but the PVMs were at a height of 1.8 m and the MET 1 was at 1.2 m. The wind and temperature instruments were at 2 m and 1.4 m respectively.

Since we were concerned to establish the effect of time domain filtering on the various outputs of the single pole devices and compare it to space domain averaging from the transmissometer, we changed all the electronic smoothing on the output stage of each instrument. This reduced the time-constant of the Mk 4 to less than 100 ms and that of the PVMs and the MET 1 to about 1 s.

All the instruments were freshly calibrated for the trial. The Mk 4 was calibrated by the technique described in Section 5.1.2.1: the PVMs and the MET 1 were set up in accordance with the manufacturers' instructions. The gain of each of the PVMs was adjusted by the use of a calibration block supplied by the manufacturer which produces a known differential signal between the detector and the reference output. The residual voltage was noted by making a visibility measurement in clean air in the laboratory. Both these measurements were re-checked at the conclusion of the experiments and small gain changes of +7 per cent for PVM A and −5 per cent for PVM B were found. In view of the fact that the instruments were stripped down and serviced in the laboratory before the initial gain measurement was made, it was thought that the changes of gain were probably due to the instruments settling down and all the computations were therefore made with the later set of gain figures.

Approximately two hours of nearly continuous data were obtained in a fog situation on 18 December 1978 and these data were recorded on magnetic tape on a Microdata 1600L logger. We believe that there were no significant aliasing errors introduced into the recorded data by the choice of sampling frequency which was 1 Hz for all the instruments. Minor breaks in the data were occasioned by automatic rewinds of the tape.

6.3. *Results*

The raw data for the 2-hour period is shown for the various instruments in the series of Figures 25 – 28. The unsmoothed output of the Mk 4, which we henceforth regard as the standard measurement of the series is in Figure 25. In view of the 40 s time-constant normally regarded as necessary for this instrument, Figure 25 is surprisingly free from high-frequency components of any significant amplitude. There is, however, some small-amplitude electronic noise and to reduce it a little and make the trace easier to study we have, in subsequent figures, applied a 2 s running-mean filter to this data.

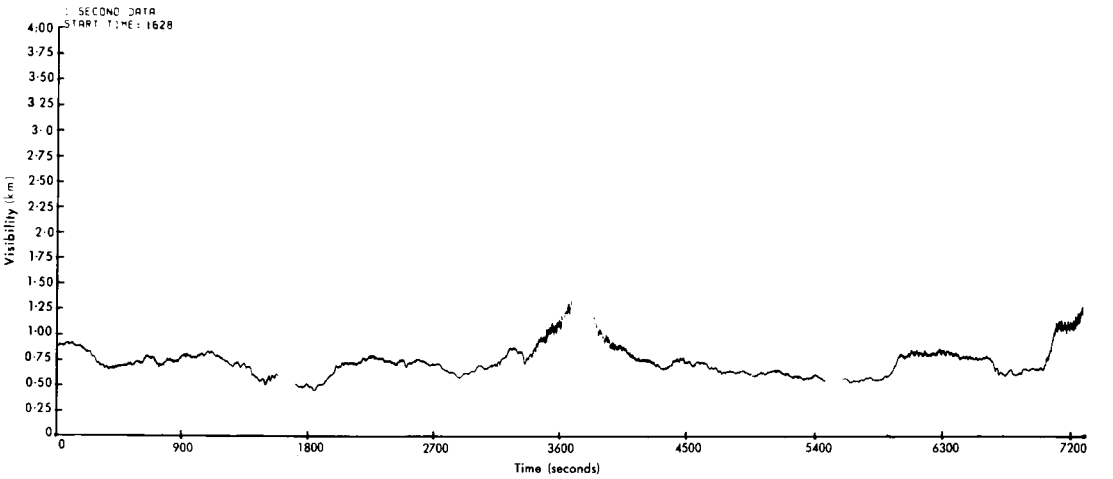

FIGURE 25. Unsmoothed output from the Mk 4 transmissometer for 18/12/78

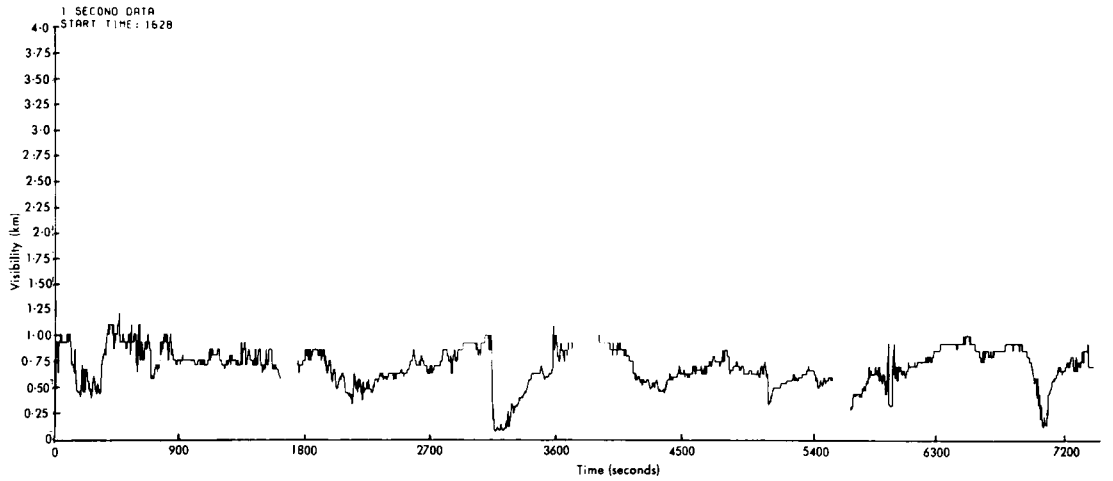

FIGURE 26. Unsmoothed output from the Marconi MET 1 for 18/12/78

A superficial glance at the raw data reveals several striking features. Whereas the mean level of the MET 1 and the Mk 4 are similar, those of the two PVMs are higher, that of PVM A being much higher. The MET 1 and the PVM A both 'see' a marked visibility feature around minutes 48 – 54 (2880 – 3240 s) which it is not obvious that the other two instruments saw. The two PVM traces show substantial high-frequency components. Results recorded in clean-air conditions from a PVM with the same time-constant of 1 s gave voltage noise levels which were about 10 per cent of the fluctuations shown on Figures 27 and 28 and from this we conclude that the variability in these data arose

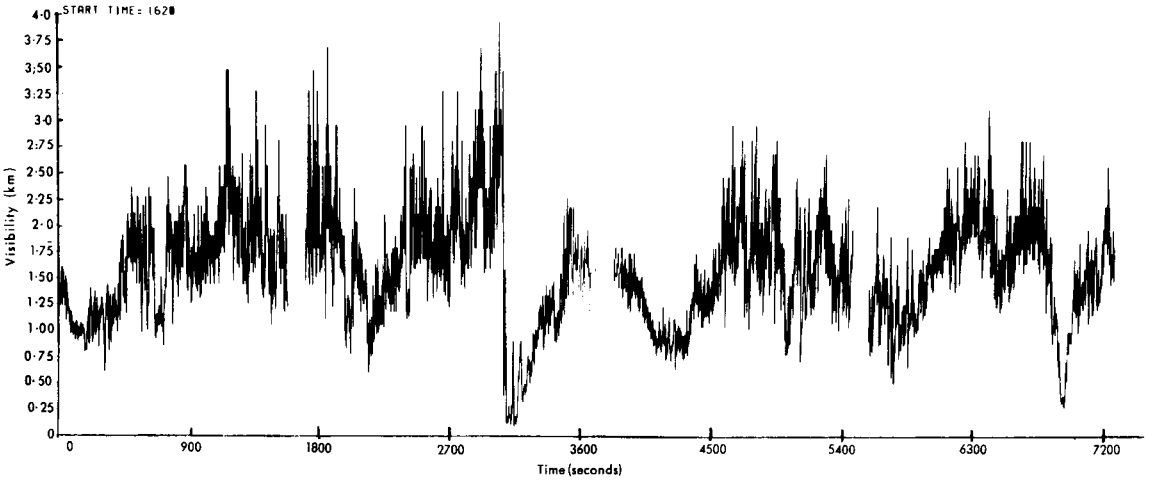

FIGURE 27. Unsmoothed output from the Point Visibility Meter 'A' for 18/12/78

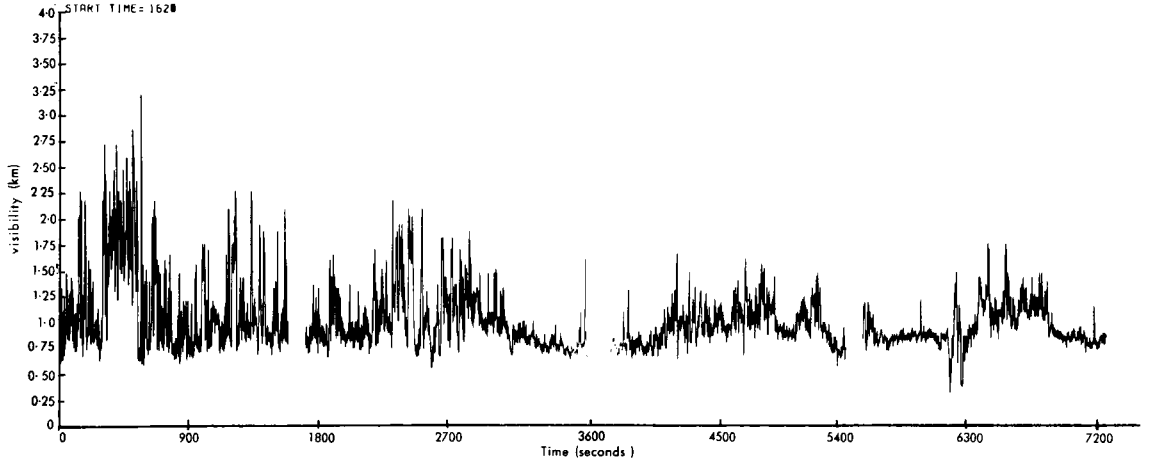

FIGURE 28. Unsmoothed output from the Point Visibility Meter 'B' for 18/12/78

because of real changes in the fog density within the sample volumes of the instruments and are not due to electronic noise.

In order to test our hypothesis that in this case temporal and spatial filtering might be approximately equivalent, it was necessary to choose a time-constant for the filter to be applied to the raw PVM and MET 1 data. To assist this choice, a quantitative analysis of the frequencies which dominate this visibility data was performed by Fast Fourier Transform methods. For this purpose, small breaks in the data were assumed not to exist. This does not introduce any particular discontinuity and the resulting data set is no less valid than if interpolated values had been inserted into the data breaks.

The amplitudes showed great variations across the spectrum, though a predominant feature of them all was a wave with a period of about 17 minutes. The two transforms which showed the greatest similarity of peaks and troughs were those of the MET 1 and PVM A in the range of periods from 5 to 40 minutes. This gives some confidence that the technique described real atmospheric variations since these dissimilar instruments were nearly co-sited.

The original transform was performed in 1.47×10^{-4} Hz steps across the frequency range 1.47×10^{-4} Hz to 5×10^{-1} Hz, giving amplitudes A_{ij} but, to reduce the complexity of these results, amplitudes A_{ik} were calculated for each instrument, i, over the wider frequency interval $5 \times 1.47 \times 10^{-4}$ Hz from the formula

$$A_{ik} = \frac{\overline{Vis_4}}{\overline{Vis_i}} \sqrt{(A^2_{i,j=5k+1} + A^2_{i,j=5k+2} \ldots\ldots + A^2_{i,j=5k+5})}$$

for $k = 0, 1, 2 \ldots\ldots$

A_{ik} thus represents the total amplitude (the sum of the individual power components) over a bandwidth $5 \times 1.47 \times 10^{-4}$ Hz from a frequency equal to $(5k + 1) \times 1.47 \times 10^{-4}$ Hz to $(5k + 5) \times 1.47 \times 10^{-4}$ Hz. The A_{ik} are also normalized so that the mean visibility for the whole period $\overline{Vis_i}$ is the same as that for the Mk 4, $\overline{Vis_4}$. The A_{ik} are plotted as a function of frequency in Figure 29 in which smooth curves have been drawn through the values of A_{ik} at the mid-point of each frequency interval. From Figure 29 it can be seen

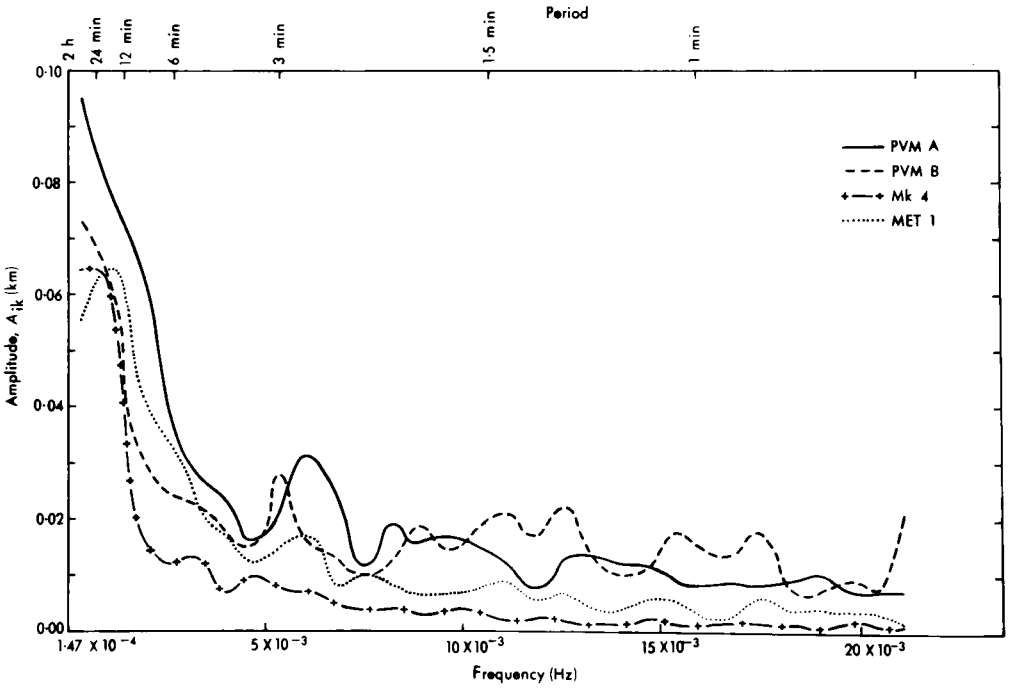

FIGURE 29. Amplitude, A_{ik}, as a function of frequency for the four visibility instruments from the records of 18/12/78

that, except for PVM A which is more variable, the instruments show similar amplitudes for periods greater than 12 minutes. Similarity of amplitudes does not necessarily mean that the instruments are recording the same features since it must be established that there is no phase difference between the functions. Nevertheless, it is clear that the Mk 4 transmissometer has a much smaller response to frequencies above 2.4×10^{-3} Hz than do the MET 1 and the PVMs and that the MET 1 shows a smaller response than the PVMs to frequencies above 8×10^{-3} Hz.

These results suggest that if the various outputs are in phase the application to the PVM data of a low-pass filter with a time-constant around 10 or 15 minutes might enable the performance of the PVM to approach that of the Mk 4. Such an average time does not seem unreasonable for synoptic purposes, though information over periods of the order of one minute might be useful to identify the uniformity of fog.

In view of these results, we computed a 600 s running mean of the PVM and MET 1 data in terms of extinction coefficient and, after conversion to visibility, compared the results with the two-second filtered Mk 4 data in Figure 30. The wind speed and direction data taken at one-second intervals at Site A is shown on the same horizontal scale. Breaks in the data have been treated by interpolating values along a straight line joining the last valid data point before the break and the first after the break.

From Figure 30, the general agreement between the Mk 4 and the MET 1 is quite striking, with only an apparent phase lag between minutes 24 and 36 and the marked features between minutes 48 and 63 distorting the agreement. The most notable disagreement seems to be that the MET 1 undermeasured the peak seen by the Mk 4 at about minute 63, but this could reasonably be explained by the difference in height of the two instruments. The Mk 4 shows a definite decrease in visibility at the same time as the MET 1 and PVM A show a marked decrease (minute 48) but it begins to recover almost at once and reaches a higher peak than the MET 1 at about minute 63. We can tentatively suggest that the sharp feature seen by the MET 1 and PVM A was either a low-level phenomenon, only partially seen by the Mk 4, or that it was a feature which was large enough in horizontal scale to envelop the MET 1 but small enough to represent only a minor perturbation to the Mk 4. In either case the MET 1 could have continued to be affected by the denser patch as the general visibility recovered. It is, however, difficult to reconcile this with the fact that the co-sited PVM A saw very well both the change and the magnitude of the recovery indicated by the Mk 4.

The general agreement between PVM B and the Mk 4 does not at first sight seem very good but careful comparison shows that apart from the trough/peak pair on the PVM B trace between minutes 54 and 86 being shallow, and out of phase, and the general level of measured visibility being too high, there is some agreement in the trends over the rest of the period. This is emphasized in Figure 31 which shows the smoothed outputs of all the instruments normalized so that their mean extinction coefficients over the whole period equal that of the Mk 4. Only between minutes 40 and 72 do the two now markedly disagree. It is clear that the PVM B did not see either the marked decrease in visibility seen between minutes 48 and 54 by PVM A and the MET 1 nor the marked recovery and subsequent decline seen by all the other instruments between minutes 56 and 72. PVM B, however, was sited well away from Site A at the south-eastern end of the Mk 4's base line, hard by a group of trees. Therefore, if these visibility features were local and if the wind

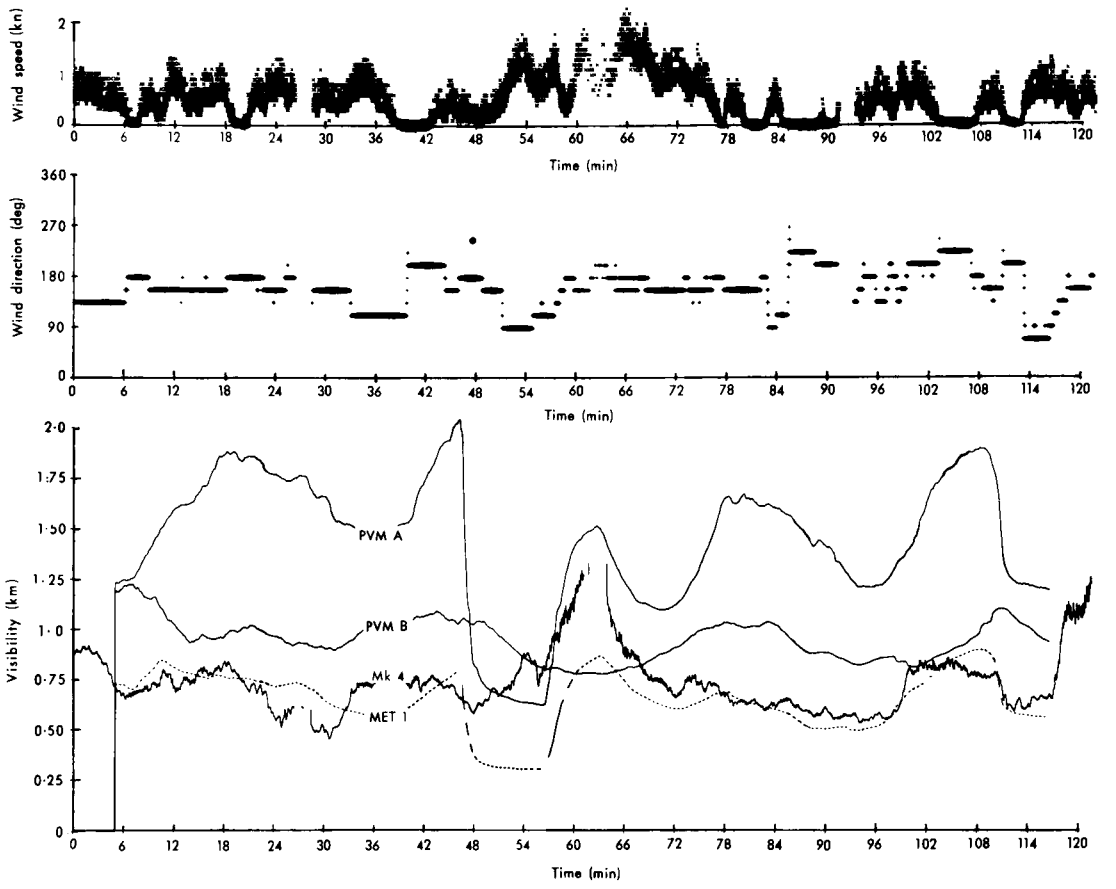

FIGURE 30. Mk 4 transmissometer output with 2-second smoothing compared to MET 1, PVM 'A' and PVM 'B' outputs smoothed with a 600-second running mean (averaging applied to extinction coefficients) and wind speed and direction from site A.

direction between 090° and 180° was generally applicable to all the instruments, it is not perhaps too surprising that they did not affect PVM B.

The general offset between PVM B and the Mk 4 which persisted throughout most of the period can hardly be explained as a local effect, particularly since the PVM follows the Mk 4 trends quite well. Given the method and attention given to the calibration of all the instruments for this experiment, this offset is unlikely to be due to a calibration error. A possible explanation might be the modification of the fog by the instrument in very light winds, but we have no wind data for Site B and in the conditions of very variable wind and differences in site which pertained in this experiment, even the nearby Site A cannot be regarded as having a similar wind speed regime.

In the case of PVM A, we do have the necessary wind data to examine the systematic difference between it and the Mk 4 in terms of the modification theory. From Figure 30 it is clear that the only time that the PVM A output approached that of the Mk 4 in absolute

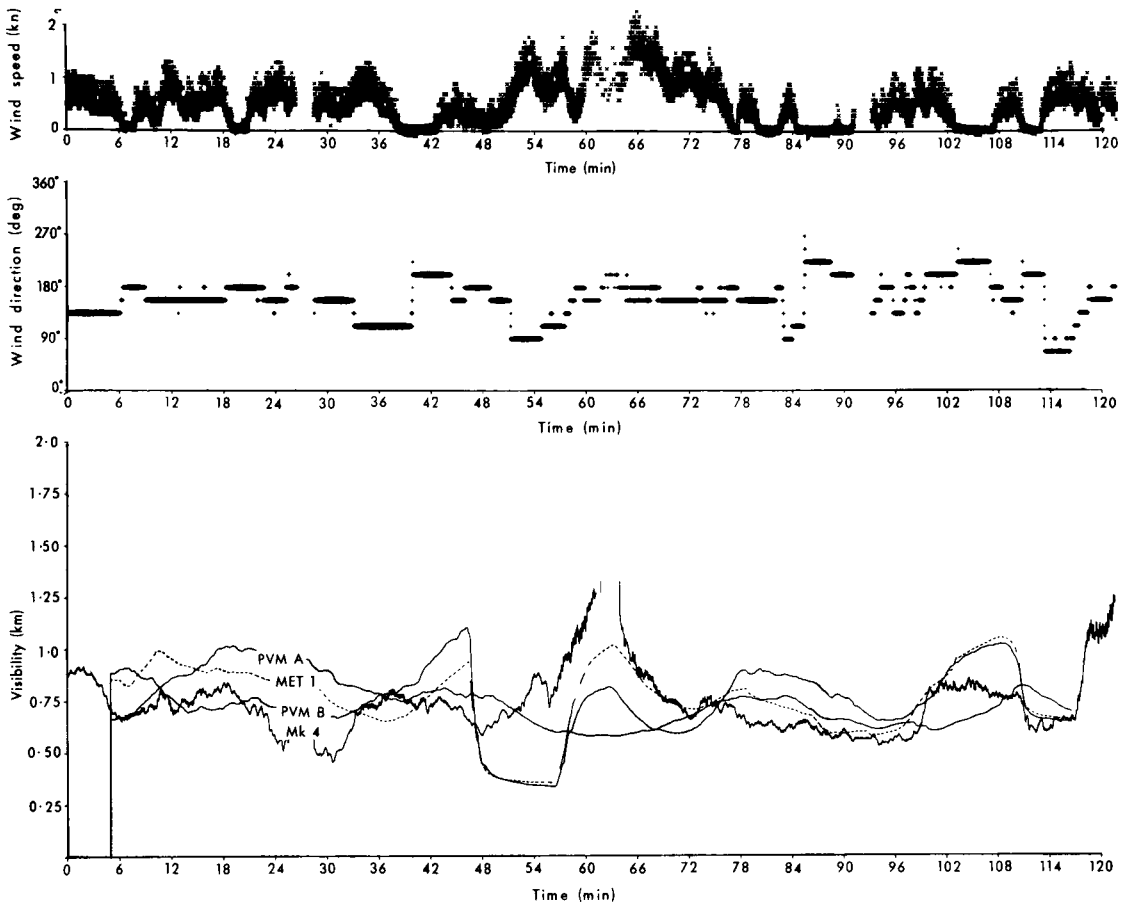

FIGURE 31. As Figure 30, but with all mean extinction coefficients over the period normalized to that of the Mk 4 transmissometer

terms was between minutes 49 and 68 which is the only period when the wind sustained a speed above 1.0 kn for more than a minute or two. At all other times, although, as Figure 31 indicates, the trends were reasonably well followed, the inverse correlation between wind speed and PVM-measured visibility has led to a significant positive error in the PVM output. The size of this error is substantial, amounting to almost a factor of two in visibility or one half in extinction coefficient. From the equations of section 5.4.5 and the results of Table IV, we can estimate the net power gain of the PVM for this case when the wind speed was around 0.5 kn and the air temperature was about 0 °C. From equation (11) of 5.4.5 we have, neglecting radiative effects,

$$\frac{\mathrm{d}h}{\mathrm{d}V} = KP_C \Big/ \frac{\mathrm{d}V}{\mathrm{d}t}$$

and from section 5.4.5, $K \approx 1.0 \times 10^{-2}$. From Table IV P_C must, in equilibrium conditions, be about -2.5 W so that from

$$\frac{dV}{dt} \approx \frac{Av}{2} = \frac{7 \times 10^{-4} \times 2.5 \times 10^{-1}}{2} \text{ m}^3\text{s}^{-1}$$

we have

$$\frac{dh}{dV} \approx -\frac{1.0 \times 10^{-2} \times 2.5 \times 2}{7 \times 10^{-4} \times 2.5 \times 10^{-1}} \approx -286 \text{ J m}^{-3}$$

If the heat transfer to the fog droplets was 100 per cent efficient and the evaporation time was short compared to the residence time of the droplets in the PVM aperture, the water evaporated by this heat transfer would be 1.1×10^{-4} kg m^{-3}. Such a loss of water content would, as is pointed out in section 5.4.5, result in the complete dispersion of the fog within the PVM sampling volume and, for a relatively thin fog such as we observed, the mechanism could almost certainly account for the large errors which we observed in the PVM measurement of visibility.

6.4. *Conclusions*

The analysis of the results of Figures 25 – 31 is complicated by the convolution of many complex factors but, even given the caution which this fact generates, we feel that we can draw several conclusions with reasonable confidence but that on the other hand some unanswered problems remain.

Firstly, we believe that the evidence of Figures 30 and 31 shows that, in rather general terms, our hypothesis is valid and that a rapidly sampled data stream from an unsmoothed PVM or MET 1 output can, by the application of a simple running mean filter with a time-constant of 600 s, approximate quite closely to the spatial average provided by an unsmoothed 200 m base-line transmissometer. It is clear, however, that marked local effects will always be liable to distort this agreement for periods of time which, at least in the circumstances we studied, would be expected to be reasonably short. The choice of the time-constant for the filter may well be dependent upon the prevailing meteorological circumstances but we probably dealt with one of the most variable conditions likely to occur and our choice of 600 s, indicated by the dominant period of the power spectra of the instrumental output, will probably be adequate for all but the most unusual cases.

Secondly, although by suitable filtering the changes in the PVM output can be shown to resemble those of the Mk 4, in conditions of fog and light winds the instrument significantly affects the measurement it is making such that under these conditions errors of up to a factor of two can be expected in the indicated visibility. We have been able to indicate the mechanism for this error but the magnitude of the problem on a particular occasion is governed greatly by the water content of the fog and the size distribution of the fog droplets and would be very difficult to predict. Measures which would reduce the problem would be to reduce the electrical dissipation of the instrument, decrease its thermal capacity and improve its ventilation.

Thirdly, we conclude that by smoothing the output of the 1 Hz data stream from the MET 1, it also produced a reasonable approximation to the unsmoothed Mk 4 transmissometer output. Like the PVM it is inevitably affected by local effects which will occasionally lead to significant differences from the Mk 4 but, as with the PVM, these

could normally be expected to be reasonably short-lived. It does not, however, suffer the defect of modifying the fog it sees and the filtered output obtained from the device in this experiment would have represented a reasonable measure of the visibility for synoptic purposes.

The principal unanswered problem lies in the marked difference between the results from the two PVMs. Although the results from PVM A can be well explained, there was insufficient evidence to provide a convincing reason for the much lower mean visibility measured by PVM B. The failure of all but PVM A to measure fully the marked peak in the visibility shown by the Mk 4 at around minute 63 has also not been convincingly explained although, as with the systematic differences between the PVMs, there are one or two plausible possibilities for it.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. *Conclusions*

The detailed conclusions of this report have been set down at the close of each section; however, the most important of them are brought together here under a single heading as a matter of convenience. They divide into three categories: those that apply to the Mk 4 transmissometer, those that apply to other transmissometers and those that apply to scattering instruments.

7.1.1. *The Mk 4 transmissometer*

We conclude that if it is carefully calibrated in the manner which we recommend then the Mk 4 transmissometer will provide an estimate of visibility which is at least as useful as that provided by a trained observer during daylight and more useful at night for the visibility range from 100 m to 10 km. Below 100 m and above 10 km it is insensitive and liable to yield a substantial fractional error in its output. We further conclude that the present method of calibrating the Mk 4 is unsatisfactory and can lead to significant distortion of its performance at the high end of its visibility range. A better calibration procedure has been devised and is recommended below.

7.1.2. *Other transmissometers*

From our results we are satisfied that in principle the Marconi MET 1 is generally capable of producing estimates of visibility in the range 100 m – 5 km that are comparable with those of an observer. Any device which makes measurements over a path as short as 2 m is bound to be affected on some occasions by purely local changes in conditions. However, we have demonstrated that by sampling the unfiltered output of the MET 1 at a frequency of 1 Hz and then filtering this data with a simple running mean with a time-constant of 600 s, all but the most marked of these local effects can be smoothed out and the resulting measurement is a close approximation to that which is made by an unsmoothed 200 m base-line transmissometer. We therefore believe that the operational uncertainty which will attach to an individual estimate from a properly set up, calibrated and maintained MET 1 of the type we used in this way should not usually exceed that of

the Mk 4 transmissometer. It is difficult to adjust the optical alignment of the MET 1 in its present form and some design modifications are needed before it could sensibly be used as an operational instrument. As with all transmissometers, including the Mk 4, it is liable to produce incorrect results during and after snowfall because accumulations of snow cause blockages in the optical path. Furthermore insects, particularly spiders, can be a source of faulty performance, though this is not as severe a problem with transmissometers as it is with scattering instruments.

The Erwin Sick SM 414 that we tested did not yield a satisfactory operational performance. The uncertainty about the true optical path length and the temperature sensitivity of the device together resulted in a large operational uncertainty. But we cannot conclude that in principle such an instrument could not be designed and manufactured to a standard that would yield results as good as those of the Mk 4 or the Marconi MET 1.

It is clear from our results that any transmissometer which is to be used on unattended sites for sensibly long periods must include, either in hardware or software, a self-generated compensation to allow for contamination of the optics. Transmissometers are particularly susceptible to errors from this cause and these errors can rapidly become very large unless they are compensated.

7.1.3. *The scattering instruments*

Neither of the two scattering instruments tested could be used on operational unattended sites and give results in which the user could have reasonable confidence. The M.R.I. Fog Visiometer was the subject of only limited tests but the results from them were not satisfactory and indicated significant problems with the device.

The PVM was studied extensively. It proved useful for visibilities between 1 km and 5 km but for visibilities below 1 km it suffers from serious instrumental problems. It is much more seriously affected by spiders than any of the other devices which we studied, mainly because spiders seem to find it so congenial, and if it fails it does not fail 'safe'. As with the short-base-line transmissometers, the PVM output can sometimes be dominated by purely local effects, but rapid sampling of the unsmoothed output and the application to it of a 600 s running mean successfully removed all but the most marked of these. Under such circumstances the filtered PVM output matched the changes in the unsmoothed Mk 4 output quite well but the absolute value of its results in fog were seriously in error during periods of light winds because the instrument significantly modifies the fog that it sees. The significant deterioration in performance associated with the use of the PVM in precipitation of all types (see 5.4.4) is also a serious shortcoming of the instrument. Against these problems, it has the advantage that its calibration is not affected by slow accretive contamination of its optics, an effect which, if uncorrected, leads to large errors in transmissometer measurements.

7.2. *Recommendations*

7.2.1. The length of time taken to complete the work reported here has been very considerable. This is partly because of the need to run such a field trial for as long as it takes to obtain representatively large data sets over the whole range of meteorological conditions and partly because such data sets when complete are very large and complex.

Our first recommendation, therefore, is that such an experiment as this should not be attempted again unless its objectives are more limited and more carefully defined at the outset.

7.2.2. As a consequence of our studies, we strongly recommend that the calibration procedure for the Mk 4 transmissometer should be revised along the lines indicated in subsection 5.1.2.1 and that the practice of 'one shot' adjustment of the amplifier gain should cease at once.

7.2.3. For the future of visibility measurement we recommend that Mk 4 transmissometers, perhaps with electronic noise and drift discrimination in the form of a chopped signal and phase sensitive detection, should continue to be used at as many manned sites as possible and that at least at night the reported visibility from such stations, except in significantly in homogeneous situations, should be that indicated by the Mk 4 rather than the observer's estimate.

7.2.4. For use on unattended sites a short-base-length transmissometer of the Marconi MET 1 type used in the manner described in section 6 will prove almost as effective as a Mk 4 on a manned and much more effective on an unmanned site and this solution should be adopted in preference to any based on scattering principles.

7.2.5. The PVM appears to suffer from a serious instrumental weakness and cannot be recommended for use as a fog measurement device until some means has been found to mitigate the problem of heat transfer to and from the instrument modifying the fog it is measuring. The serious problems with precipitation measurements and spiders also severely limit its usefulness.

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